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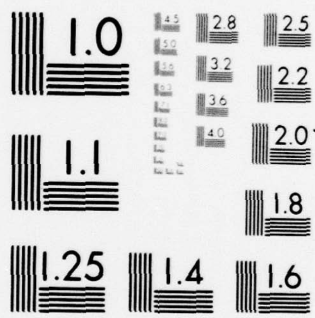
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THERMAL RESPONSE TURBINE SHROUD STUDY

E. J. KAWECKI

Pratt & Whitney Aircraft Group
P.O. Box 2691
West Palm Beach, Florida 33402

July 1979

TECHNICAL REPORT AFAPL-TR-79-2087
Final Report for Period August 1978 - May 1979

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This technical report has been reviewed and is approved for publication.

Charles W. Elrod

CHARLES W. ELROD
Project Engineer

FOR THE COMMANDER

Ernest C. Simpson

ERNEST C. SIMPSON
Director
Turbine Engine Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The program objective was to evaluate active clearance controls (ACC) for future military fighter and transport aircraft/engines, rank the candidate schemes, and recommend a future course of action.

Fifty-one potential ACC concepts were reduced to twelve: five mechanical, two pneumatic, and five thermal.

The fighter and transport missions selected were the Advanced Tactical Fighter (ATF), and the C141X strategic aircraft. → next page

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Three levels of controls for ACC were considered: simple on/off two-position; open loop infinitely variable; and feedback (requiring a clearance sensor). On/off systems were selected for study because the majority of the benefit is obtained during cruise/dash and the open and feedback systems have positioning and reliability uncertainties.

The criteria selected to evaluate the different schemes were net Life Cycle Cost benefits ~~(ΔLCC)~~ to the fleet over the life of the weapons system. These criteria were based on a new-engine/new-aircraft application where efficiency improvements due to ACC were used to reduce aircraft and engine size for a fixed mission (range, payload, etc.). The detailed operation and impact (cost, weight, reliability, maintainability) of the twelve final schemes were evaluated by adopting each of the candidate schemes to selected stages in the base engines. The effectiveness and net payoff of each scheme on each engine were evaluated for the ~~HPC~~, HPT, and LPT.

ACC showed a significant net benefit in the transport high pressure turbine. On the low pressure turbine some schemes showed a net ~~ΔLCC~~ savings, but the amount ~~of the savings~~ was small.

For the fighter application, ACC showed a significant net benefit in the high pressure turbine only.

FOREWORD

This report describes the work performed by the Pratt & Whitney Group, Government Products Division of United Technologies Corporation, West Palm Beach, Florida 33402, under U.S. Air Force Contract number F33615-78-C-2022. This is a final report covering all program efforts.

The Government Technical Manager for this period was Mr. C. W. Elrod of the Air Force Aero Propulsion Laboratory WPAFB (Telephone 513-255-2121) who provided the technical direction for the Air Force portion of the program.

The project was coordinated at Pratt & Whitney Aircraft under the direction of Dr. E. J. Kawecki, program manager. Appreciation is extended to the many design personnel for their assistance on this program and to E. M. Beverly, M. J. Wallace and J. R. Miner for their engine knowledge and advisory support.

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SECTION 1
INTRODUCTION

1.1 INTRODUCTION

Effective gas path sealing is a fundamental and continuing problem in aircraft gas turbine engines. The trend to higher cycle pressures and temperatures in advanced engines and concern over ever decreasing petroleum supplies make the efficiency improvements resulting from better sealing a significant factor in future engine designs.

These improvements must, however, be balanced against the inherent increased complexity, cost, and weight of improved sealing systems to ensure that maximum net system benefit is achieved.

1.2 STATEMENT OF THE PROBLEM

Clearances between rotating and stationary elements in the primary gas path are detrimental to engine performance (TSFC, TIT and surge) in the range presently encountered. To reduce this penalty the engines are designed to minimize the clearances at critical operating conditions.

Significant dimensional changes are encountered however, in both the rotating and static components during engine operation. Centrifugal loading, temperature changes and maneuver or landing loads all result in dimensional changes or deflections which are generally large in comparison with desired running clearances.

The clearances can be set as desired at only one operating point in a conventional passive design. In such a design engine durability requires that they be set to minimize any anticipated rub at the most severe flight point encountered. Typically this point occurs during a mission transient (takeoff, combat, or maneuver), which results in clearances being larger than desired during the remaining portions of the flight. The need for improved clearance control arises because the overall mission efficiency is generally weakly dependent on clearances at the most severe flight point and is strongly dependent on the unavoidably open clearances at the less severe points (cruise).

The problem is to develop more responsive clearance control throughout the flight envelope resulting in maintaining the clearances at their optimum level during those portions of the mission where efficiency is important. To accomplish this it is necessary to design and control the relative positions of adjacent rotating and static parts of sealing systems on important components of the engine. Because of the dynamic nature of the gas turbine engine, Active Clearance Control (ACC) is a promising method of accomplishing this.

Improvements in clearance control can be of the passive or active type. Passive control includes features designed to better match the rotor and stator growth throughout the mission. When this approach is used, however, the desired clearance can still only be set at one and only one mission point. Clearances at other points can be reduced through the use of materials with low coefficients of thermal expansion by using vane tied configurations and by tailoring internal cooling, for example. These systems cannot, however, be used to independently set a desired clearance.

ACC encompasses all techniques where the clearances can be independently set as desired at more than one mission point.

1.3 OBJECTIVES

The objectives of the program were to evaluate a comprehensive cross section of ACC concepts and establish a systematic ranking procedure to determine the relative merits of each concept. The evaluation and ranking of the ACC concepts was dependent on the type of engine (high bypass ratio or low bypass ratio), the aircraft, mission, flight envelope (fighter, transport), and the factors of reliability, maintainability, complexity, procurement cost, performance (fuel savings) and Life Cycle Cost (LCC). From the resultant rankings, a limited number of concepts for each engine type and flight envelope were recommended for further evaluation in a follow-on program.

1.4 TECHNICAL APPROACH

A program flow chart outlining the technical approach and key program items is given in Figure 1. A detailed discussion of each program item is discussed in the appropriate subsections of Section 2, "Technical Program."

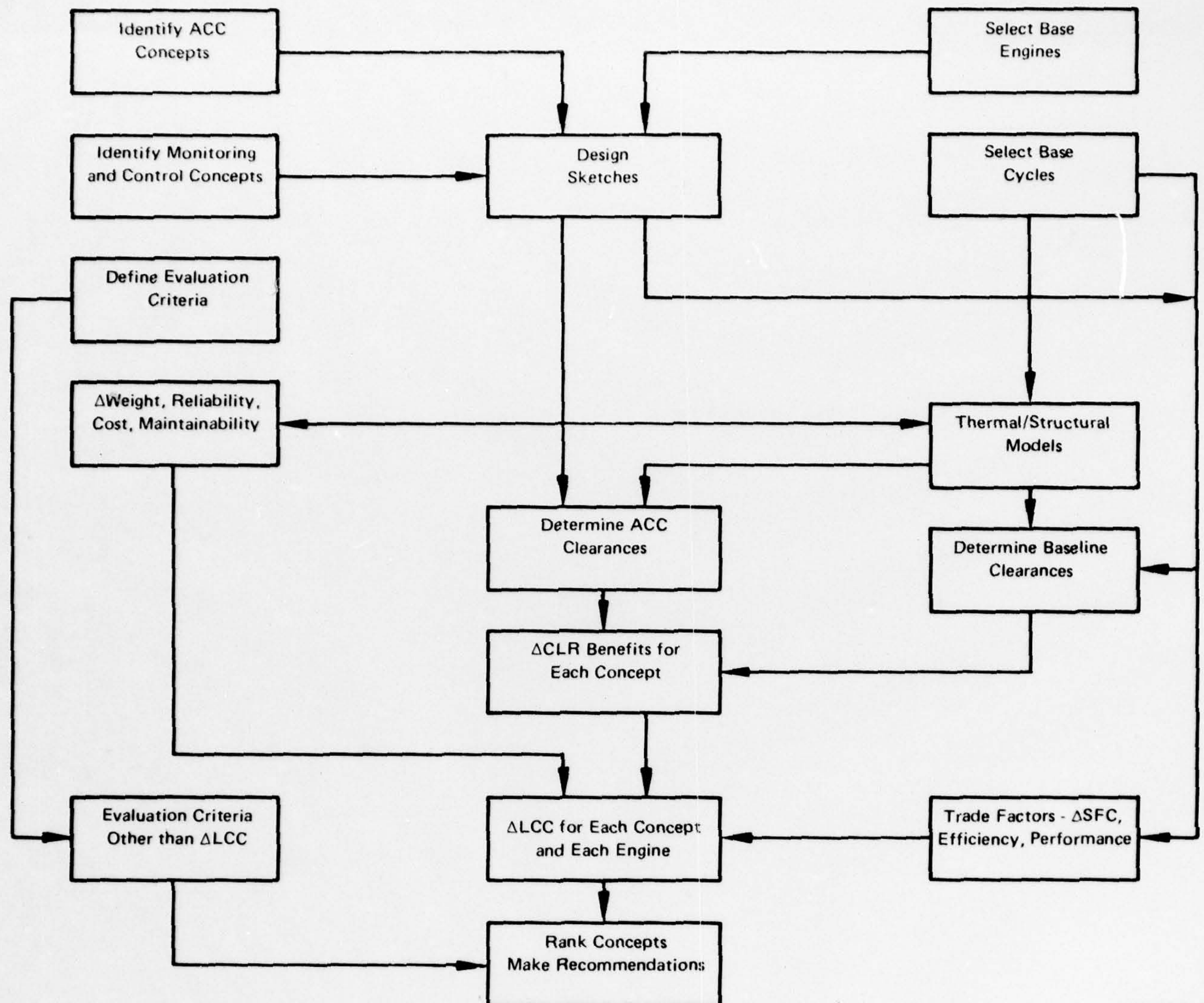

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Figure 1. Program Flow Chart

SECTION 2
TECHNICAL PROGRAM

2.1 IDENTIFICATION OF CANDIDATE CONCEPTS

A comprehensive search for ACC ideas and schemes was performed in order to generate a comprehensive selection of ACC techniques for evaluation in the study.

2.1.1 Compilation of Candidate Schemes.

Reviews of the open literature, Pratt & Whitney Aircraft Group literature, in-house brainstorming sessions, and search of the U.S. patent archives identified 51 schemes and variations of schemes designed to control clearances in rotating machinery. All potentially applicable schemes were retained during this phase.

Reviews of the open literature were conducted through the Defense Documentation Center and NASA Scan Literature Search services. The NASA service revealed 80 related items, of which 9 were generally applicable to this work. These documents were primarily related to clearance measurement and none were specifically concerned with devices or schemes to actively control component blade tip clearances. The Defense Documentation search identified 58 publications in the general area of machinery clearances. Only 3 were of interest to this contract, and all 3 of these dealt with tip clearance measurement. No devices or schemes to actively control component blade tip clearances were uncovered.

A search of the U. S. Patent archives identified 33 related patents, of which the 13 listed in Table 1 were directly applicable to this work and were considered as candidate schemes. A review of P&WA literature and in-house brainstorming sessions identified 41 other schemes or variations. These schemes, along with the schemes identified by the patent search, are listed in Table 2 and illustrated in Figures 2 through 50. A description of the operating principles of each scheme and comments on the practical consequences of its application to an engine are given along with the illustrations in Section 2.1.2.

The number and variety of schemes uncovered presented a comprehensive selection on which to base a representative and thorough evaluation of ACC for military fighter and transport aircraft.

2.1.2. Description of Candidate Schemes

Scheme No. 1. Cantilever Stator Tip Control — Variable Stator. The cantilever stator actuation scheme uses a lever and sync ring actuated cam at the base of the stator to change the clearance. Rotating the stator ramp causes the stator to move radially inward closing the gap.

The scheme is shown in Figure 2 and requires the vane angle and clearance to be coupled, but these are not dependent in general. Therefore, the scheme is not practical as shown, but can be modified for use on fixed stators as shown in Figure 3 by:

- Supplying a unison ring and many supports to prevent shroud ovalization
- Accounting for machining tolerance, wearing of bushings, etc. Ring pins will need carbon bushings for high temperature areas
- Including extra leakage and sealing on segmented shrouds as a loss.

TABLE I. RELATED PATENTS

Number	*Title*	*Inventor*	*Assignee*	*Date*
2,863,601	Compressor Air Bleed Control	Bruce N. Torell	United Technologies Corporation	12/09/58
3,029,064	Temperature Control Apparatus for Turbine Cases	D.E.J. Buckingham	D. Napier & Son Limited	04/10/62
3,085,398	Variable — Clearance Shroud Structure for Gas Turbine Engines	James Frederick Ingleson	G.E. Company	04/16/63
3,141,651	Turbine Shroud Structure	W.B. Moyuer	G.E. Company	07/21/64
3,647,313	Gas Turbine Engine with Compressor Rotor Cooling	Bernard L. Koff	G.E. Company	03/07/72
3,736,751	Gas Control Apparatus	John Rodney Dyson Fuller	Secretary of State of Defense in Her Majesty's Govt of the United Kingdom of Great Britain and Northern Ireland	06/05/73
3,742,705	Thermal Response Shroud for Rotating Body	Perry P. Sifford	United Technologies Corporation	07/03/73
3,966,354	Thermal Actuated Valve for Clearance Control	William R. Patterson	G.E. Company	06/29/76
3,975,901	Device for Regulating Turbine Blade Tip Clearance	Claude Cristian, Hallinger, L'Hay-Les-Roses Robert Kervistin, Melun	Societe Nationale D'Etude et de Construction de Moteurs D'Aviation	08/24/76
4,005,946	Method and Apparatus for Controlling Stator Thermal Growth	Bertrand Hirsch Brown Francis Louis DeTolla Dale Robert Reilly	United Technologies Corporation	02/01/77
4,019,320	External Gas Turbine Engine Cooling for Clearance Control	Ira H. Redinger, Jr. David Sadowsky Phillip S. Stripinis	United Technologies Corporation	04/26/77
4,050,843	Gas Turbine Engine	Peter Richard Needham Kenneth Richard Langley Wooton - Under - Edge	Rolls Royce (1971) Limited	09/27/77
4,069,662	Clearance Control for Gas Turbine Engine	Ira H. Redinger, Jr. David Sadowsky Phillip S. Stripinis	United Technologies Corporation	01/24/78

TABLE 2. INDEX TO ACTIVE CLEARANCE CONTROL SCHEMES

Scheme No.	*Type*
1	— Cantilever Stator Tip Control
1A	— Cantilever Stator Tip Control
2	— Cantilevered Variable Stator with Separate Cam
3	— Axial Rotor Shift — Two Piece Screw
4	— Axial Rotor Shift — Hydraulic
5	— Axial Rotor Shift — One Piece Screw
6	— Axial Case Shift — Conical Flowpath
6A	— Axial Shroud Shift — Conical Flowpath
7	— Pneumatic Strap Tip Shroud
8	— Strap Tip Shroud
9	— Pneumatic/Thermal Variable Tip Shroud
10	— Screw Actuated Variable Tip Shroud
10A	— Screw Actuated Variable Tip Shroud/Endwall
11	— Ring/Link Variable Shroud — 3 Rings
12	— Ring/Link Variable Shroud — 2 Rings
13	— Ring/Link Variable Shroud — 2 Rings with Guide Slots
14	— Split Hoop Variable Shroud — Multiple Actuation
15	— Split Hoop Variable Shroud — Two Sections
16	— Thermal Link Actuated Shroud
16A	— Thermal Link Actuated Shroud — Improved
17	— Bellows Actuated Shroud
17A	— Pneumatic Actuated Shroud
18	— Bellows Actuated Shroud and Stator Group
19	— Thermal — Split Case Cooling
20	— Thermal — Segmented Case Cooling
21	— Thermal — Split Case Heating and Cooling
21A	— Thermal — Built-up Case Heating
22	— Thermal — Split Case Heating
22A	— Thermal — Segmented Case Heating
23	— Thermal — Bore Heating and Cooling
24	— Thermal — Bore/Rim Heating
25	— Floating — Vane and Case
26	— Thermal — Electrically Heated Shroud
27	— Thermal — Electrically Heated Rear Compressor Seal
28	— Rear Compressor Seal — Bellows Actuated
29	— Rear Compressor Seal — Pneumatic Band Actuated
29A	— Rear Compressor Seal — Band Actuated
30	— Rear Compressor Seal — Mechanical Link Actuated
31	— Thermal — Externally Cooled Cases
32	— Thermal — Cooled/Heated Shroud Supports
33	— Cam Actuated Shroud
34	— Thermal — Externally Cooled Cases — Air Deflector
35	— Thermal — Externally Cooled Cases — Insulated Air Deflector
36	— Blade Tip Erosion Compensator
37	— Axial Rotor Shift — Conical Shroud
38	— Thermal-Heated/Cooled Shroud — Passive
38A	— Thermal-Heated/Cooled Shroud — Active
39	— Thermal-Heated/Cooled Shroud — Case
40	— Thermal-Heated/Cooled Shroud/Case — with Mixing
41	— Thermal-Heated/Cooled Shroud Case — with Vane Bleed
42	— Externally Cooled Case — Air Deflector

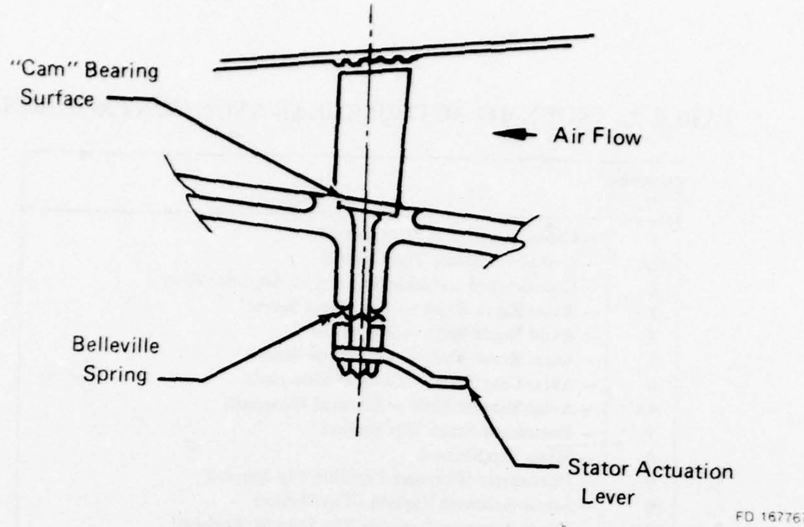


Figure 2. Scheme No. 1, Cantilever Stator Tip Control

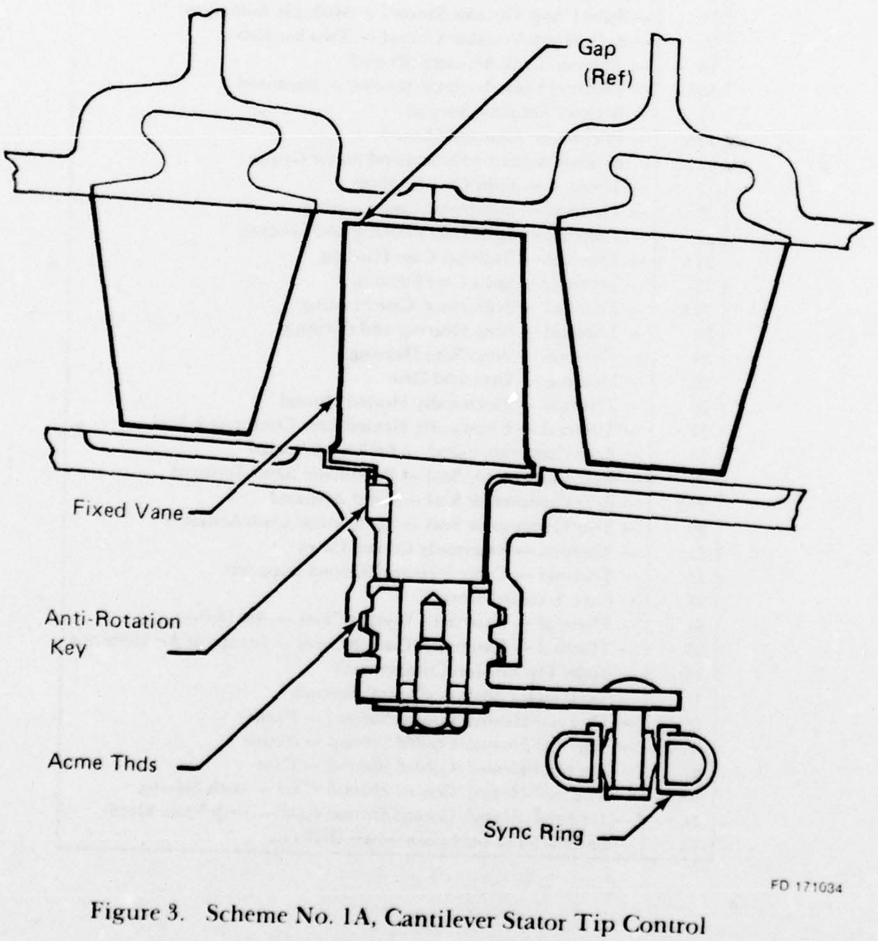


Figure 3. Scheme No. 1A, Cantilever Stator Tip Control

This scheme is satisfactory for cantilevered stators and segmented shrouded stators. It is unsatisfactory for solid ring shrouds because stators cannot transmit the required compressive load without buckling.

Scheme No. 2. Cantilever Stator Tip Control — Fixed Stator. The comments for scheme 1 apply, but in this configuration (Figure 4) the thread gives radial positioning instead of the cam, and the same unison ring actuation technique is required.

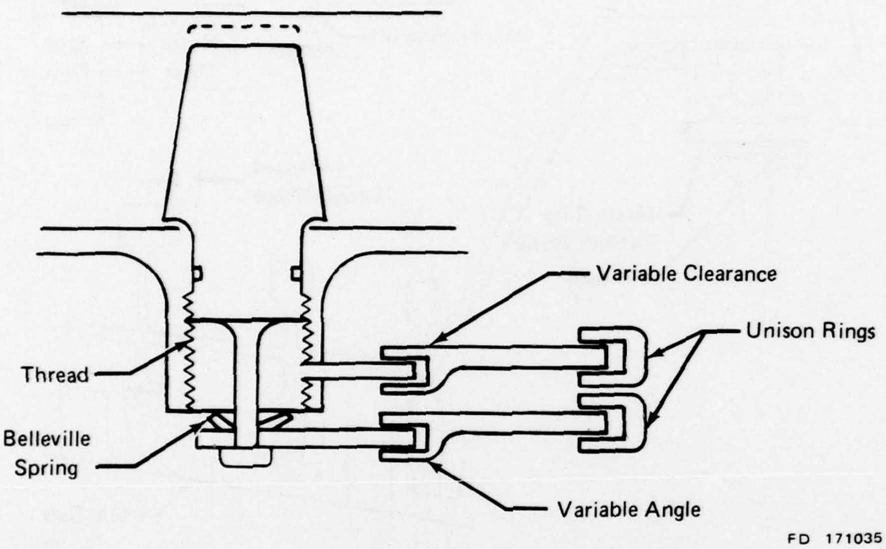


Figure 4. Scheme No. 2, Cantilever Variable Stator With Separate Cam

Schemes No. 3 through 6 involve shifting the entire rotor axially relative to the case. By specifying a conical flowpath this shift results in a clearance change.

All of these schemes are mechanically complex and are not applicable to rear compressor stages without having the compressor exit flow enter the diffuser at some angle. Losses in diffuser efficiency must be accounted for when computing gains.

Scheme No. 3. Axial Rotor Shift, Two Piece Screw. With this scheme (Figure 5), closing the compressor clearance *opens* turbine clearance if conventional converging/diverging flowpaths are used. Improving clearances in one component will hurt the other.

Accessories normally driven by a bevel gear supported by the main thrust bearing can no longer be positioned by this same bearing if the rotor is moved axially. A separate thrust bearing and sliding spline is required to support the bevel gearshaft and to transmit the torque from the main shaft. The scheme requires extra weight, cost, complexity and engine length. The engine must be longer to allow for axial clearance between stages. Assuming 5 deg and 10 deg gas path, the increased length is: 1.8 in. for 10 deg gas path angle and 0.025 in. clearance change, or a 3.4-in. increase in engine length for 5 deg gas path angle and the same clearance.

Both inner and outer surfaces of the flowpath must have the same angle (opposite sign) in order to get the same clearance change on the rotor and stator, i.e., both sides of the flowpath are completely specified for clearance alone. This may not be practical since it results in less than optimum components structurally and aerodynamically.

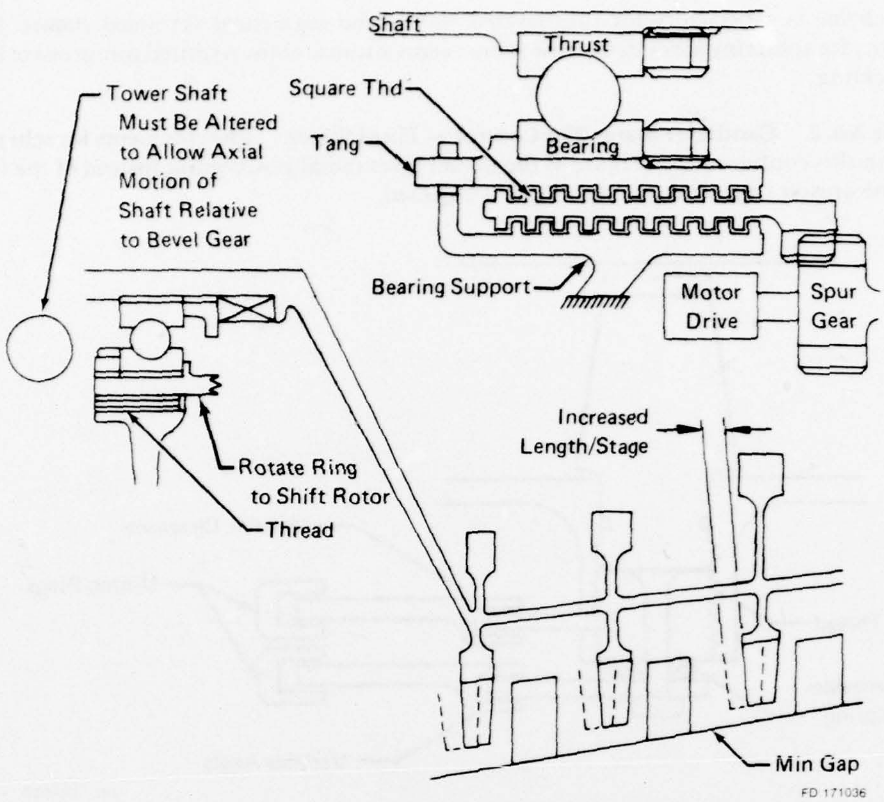


Figure 5. Scheme No. 3, Axial Rotor Shift, Two-piece Screw

The technique appears more applicable to the middle half stages of a compressor (or high turbine) where the flowpath normally has a significant angle and the vanes are not variable. Limiting it to part of a component will result in a smaller payoff, however.

The scheme can be optimized for all stages at one engine condition only. Off design operation will be less efficient, and mechanical components must be strong enough to withstand surge and maneuver loads.

Scheme No. 4. Axial Rotor Shift, Hydraulic. This is a variation of the axial rotor shift scheme, where the same comments apply as for scheme No. 3. In addition the hydraulic system must overcome thrust bearing loads (see Figure 6) and a separate oil pump is needed to supply the high pressures required to overcome rotor thrust. An oil pump must be used because fuel cannot be used in this instance.

Scheme No. 5. Axial Rotor Shift, One Piece Screw. This scheme (Figure 7) is similar to schemes No. 3 and 4. It requires one less moving part than scheme No. 3.

Scheme No. 6. Axial Case Shift, Conical Flowpath. Schemes No. 6 and 6A (see Figures 8 and 9) are analogous to schemes No. 3 through 5 in that the clearance is controlled by having a sloped flowpath and a relative motion between the rotor and stator. Schemes No. 6 and 6A move the cases, schemes No. 3 through 5 move the rotor.

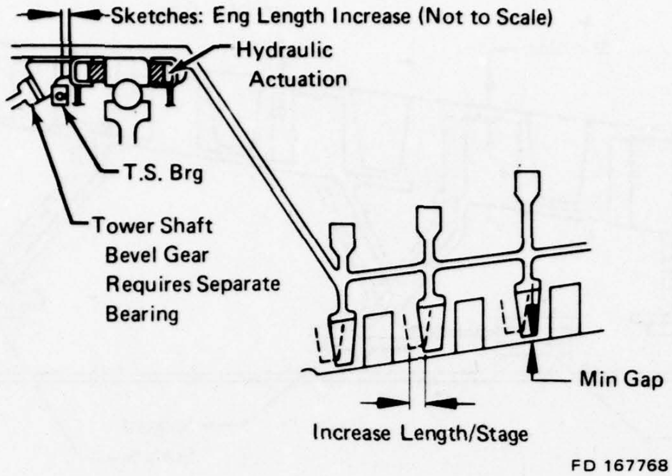


Figure 6. Scheme No. 4, Axial Rotor Shift, Hydraulic

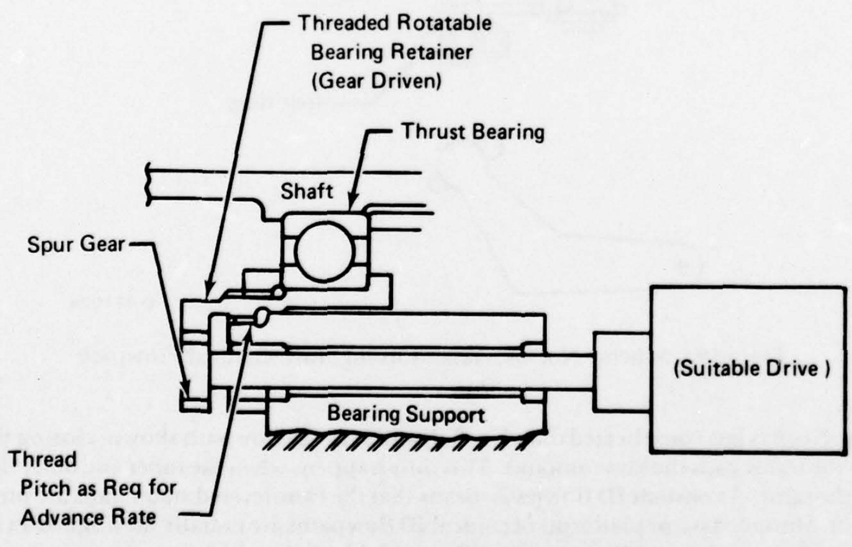


Figure 7. Scheme No. 5, Axial Rotor Shift, One-piece Screw

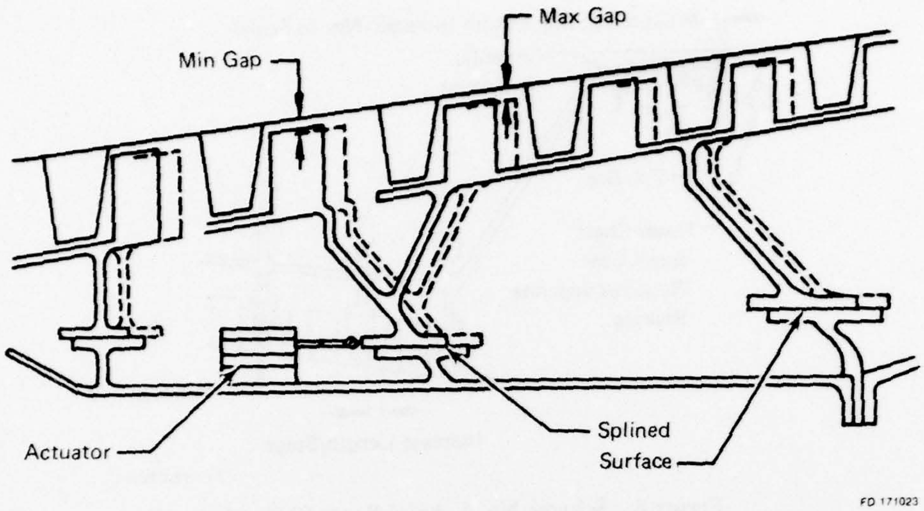


Figure 8. Scheme No. 6, Axial Case Shift, Conical Flowpath

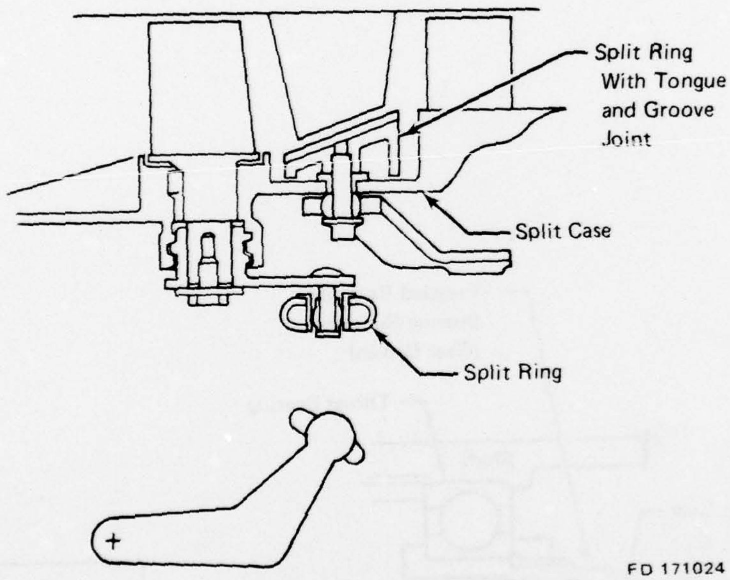


Figure 9. Scheme No. 6A, Axial Shroud Shift, Conical Flowpath

Scheme No. 6 is less complicated than No. 3, 4, and 5. In the flowpath shown, closing the rotor gaps closes the stator gaps the same amount. This only happens when the inner and outer flowpath angles are the same. A constant ID flowpath means that the cantilevered stator gaps are unaffected by rotor shift. Shrouded stator platforms of conical ID flowpaths are radially misaligned an amount equal to the clearance change. This generates flowpath blockage which must be accounted for. In addition starter bleed and anti-ice bleeds must pass through the shroud to the outer cases. Because splines cannot be pressure sealed easily, a new design feature is required, possibly a flextube between the case and shroud to release the air. The scheme can be used with shrouded stators, but it requires an additional wall (case) to support the moving structure.

The splines only serve to locate the shrouds circumferentially while the actuator takes thrust loads. High torque must be transmitted through this spline resulting in high friction and large actuation loads.

The technique eliminates the large number of moving parts required of schemes that actuate one shroud at a time; i.e., no unison rings, etc. are required. It did require a change in engine length like scheme No. 3, but unlike scheme No. 3, it does not couple turbine clearance to compressor clearance.

Scheme No. 6A. Axial Shroud Shift. The compressor shroud (see Figure 9) is a conical ring that translates forward and aft. This technique uses the same principle as scheme No. 6, but allows each stage to be controlled independently and does not require the structural case to move. The effect of gaps between ring and shroud stops outer rings and flowpath angle changes deteriorate compressor performance. Sealing to reduce recirculating losses must also be incorporated. Sliding friction at high temperatures, particularly at rearmost compressor stages, may be a problem.

Scheme No. 7. Mechanically Variable Strap Shroud. The shroud is a strap or band whose circumferential length is controlled by an actuator (see Figure 10). Reducing the circumference reduces the clearance. The scheme is best suited to two-position operation where seal concentricity and radial travel can be controlled by retaining rings in the case. For intermediate operation some method of preventing ovalization is required, possibly sloped pins around circumference to guide growth.

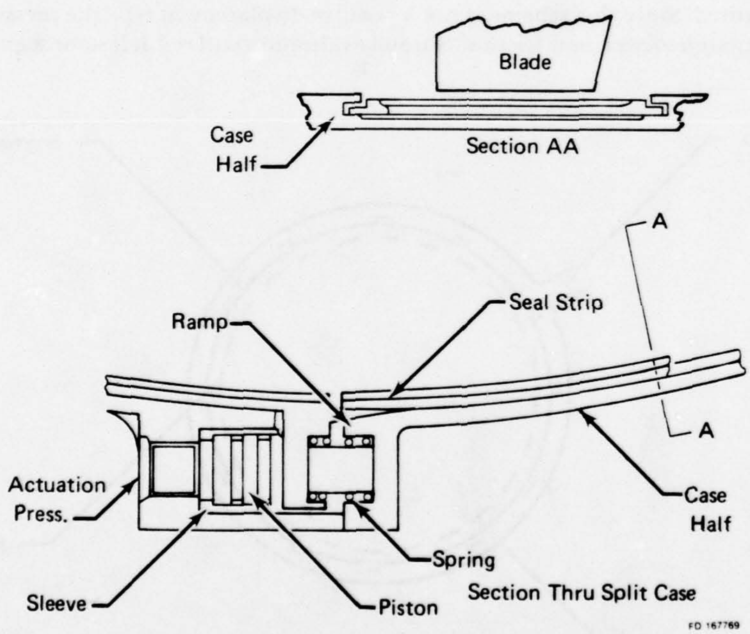


Figure 10. Scheme No. 7, Pneumatic Strap Tip Shroud

The scheme must be pressure balanced carefully and sealed against circulation leaks. This scheme is easier to seal than segmented shrouds. Return requires outward pressure from the gas path to open the ring. The piston area is small with respect to ring surface area, resulting in high actuation pressure being required to overcome area ratio. Mechanical actuation (ball and screw) would be an improvement and may be required. Actuation of the rear compressor stage would require a pressure supply considerably above compressor exit pressures; thus a compressor or pump would be required.

Scheme 8. Mechanically Variable Strap Shroud. Basically this scheme (see Figure 11) is similar to scheme No. 7 but the actuation is left undetermined.

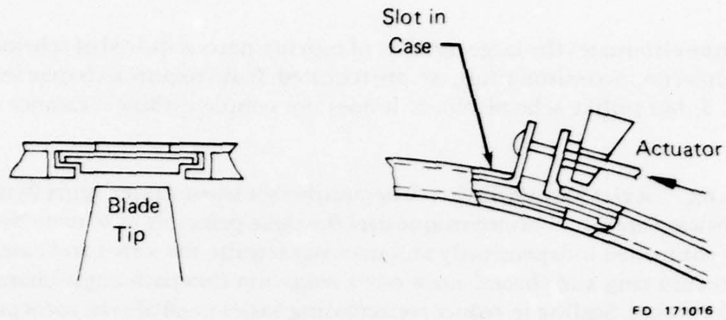


Figure 11. Scheme No. 8, Strap Tip Shroud

Actuation might be by ball screw which would provide fast response and a large actuating force, or it could possibly be hydraulically actuated.

Scheme No. 9. Pneumatic/Thermal Variable Tip Shrouds. The segmented shrouds move radially in response to back pressure changes (see Figure 12). Thermal growth may play a significant part in determining clearances. An air supply pressure significantly above local gas path pressure is required. Since this scheme is not a positive displacement type the pressure difference must be large enough to overcome friction. Shroud ovalization will result if some segments hang up due to friction.

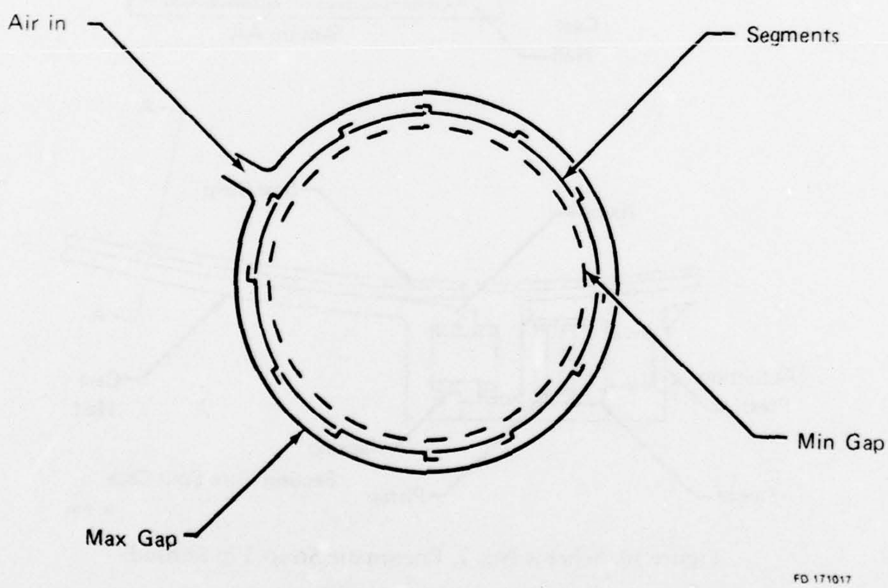


Figure 12. Scheme No. 9, Pneumatic/Thermal Variable Tip

Items of concern are the leakage and sealing between segments and the axial backflow between segment seals. The scheme is primarily two-position and is not easily modulated. Blade rubs might be the only mechanism which can force seals out which have hung up.

Schemes No. 10 and 10A. Screw Actuated Variable Tip Shrouds and Stators. The shrouds and stators are moved radially with a lever arm and sync ring driven screw, as shown in Figures 13 and 14. Stage-by-stage actuation is possible. The positive displacement of this type of scheme minimizes binding problems. Local punch loads on the ring cause it to deflect inward at load points and outward between loads, possibly inducing ovalization or limiting clearance travel. Two or more supports are required per segment. Six to eight segments are required to get 90% effective clearance change due to the fixed arc of shrouds.

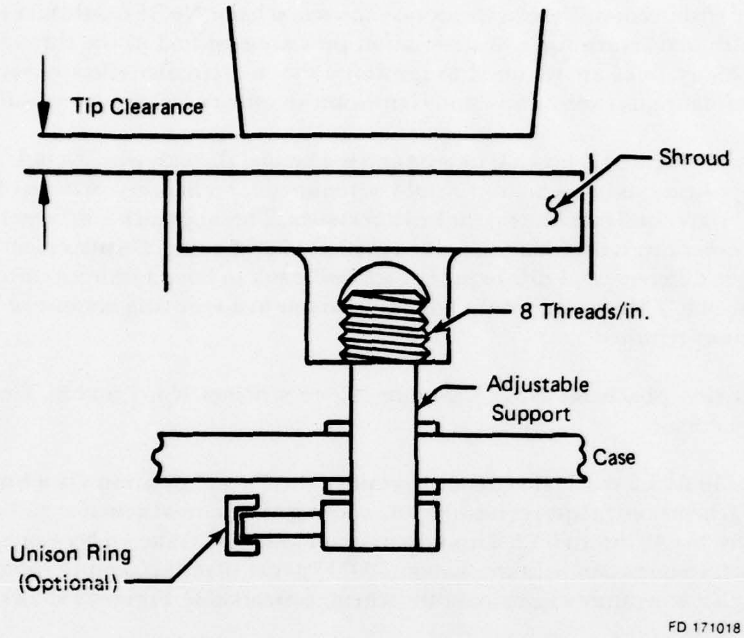


Figure 13. Scheme No. 10, Screw Actuated Variable Tip Shroud

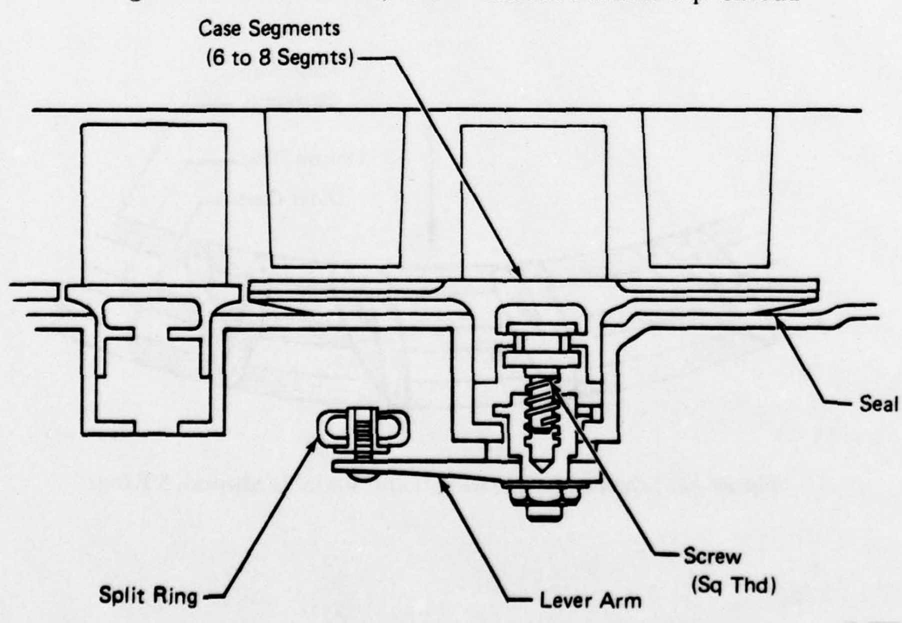


Figure 14. Scheme No. 10A, Screw Actuated Variable Tip Shroud

Mechanical Linkage Actuated Shrouds. These shroud positioning schemes use some type of mechanical lever system to position the shrouds. Single and multiple actuators tied to the cases and to the shrouds by different schemes are considered. Actuation at only a few points requires additional design to keep shrouds from ovalizing and distorting.

As a group these schemes have numerous parts and must actuate through the case thus resulting in potential sealing leaks. Manufacturing and operating tolerances would diminish the clearance control effectiveness. Use of a spring (as shown in scheme No. 16) could take up some slack and provide additional return force. Anti-rotation pins are required in the shrouds of schemes No. 12 and 16. Many links are required to minimize the non-circular effect of segmenting the shrouds and modulating between stops, and significant secondary leakage may result.

Scheme No. 13 (Figure 17) uses a sync ring and segmented shrouds with a single actuator. For typical engine applications two actuators would be required for reliability. Schemes No. 11 and 12 (Figures 15 and 16) are similar except for the linkage system. This approach is different from scheme No. 14 (Figure 18) because it uses many actuators in place of a sync ring. Displacement at each point around the ring is different, and this requires each bellcrank to have a different arm length for a given actuator stroke. This system would not be as reliable as a sync ring because of the increased number of actuators required.

For a discussion of scheme No. 15 (Figure 19) see schemes No. 7 and 8. This system has unnecessary actuators.

Scheme No. 16 uses a thermal actuator to control the shroud position via a link system (see Figure 20). The scheme only requires heating and cooling of a thermal actuator, rather than entire case as in schemes No. 19 through 22. This system is not practical as shown because short actuator (1 or 2 in.) requires a large temperature change (500° F) to get 10 mils clearance control. Materials required and high temperature source make the scheme unworkable. Figure 21 shows an improved version of the schemes.

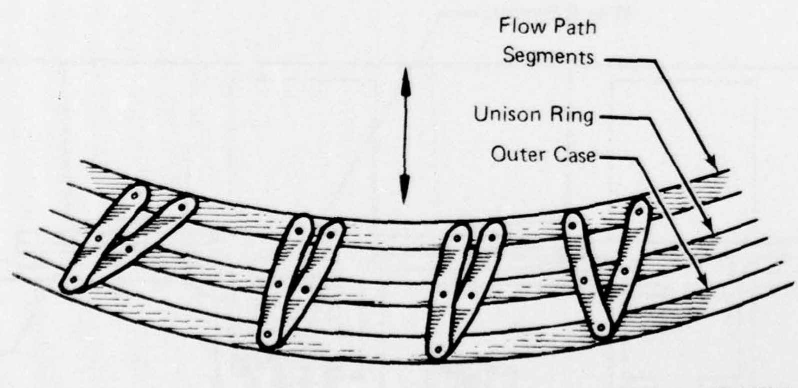


Figure 15. Scheme No. 11, Ring/Link Variable Shroud, 3 Rings

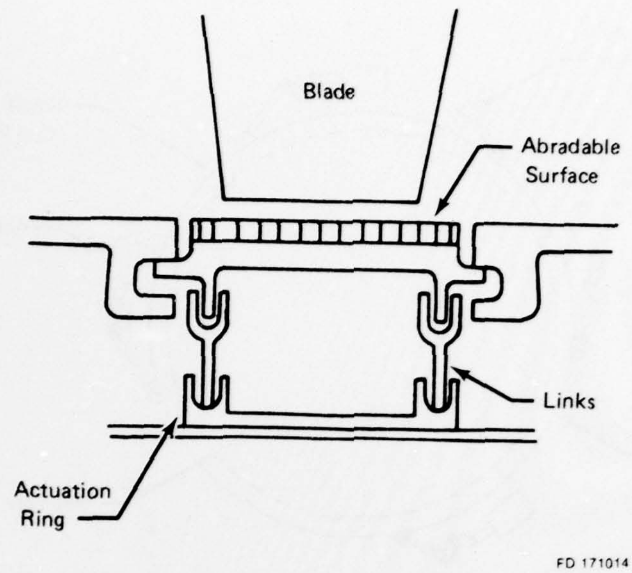


Figure 16. Scheme No. 12, Ring/Link Variable Shroud, 2 Rings

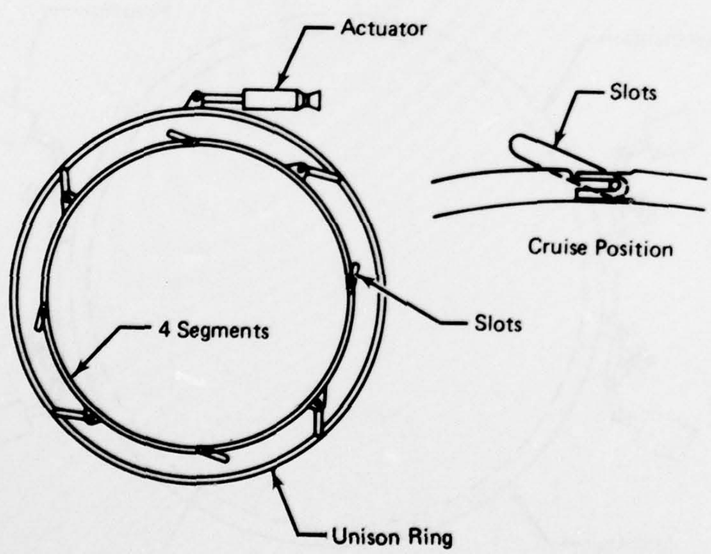


Figure 17. Scheme No. 13, Ring/Link Variable Shroud, 2 Rings with Guide Slots

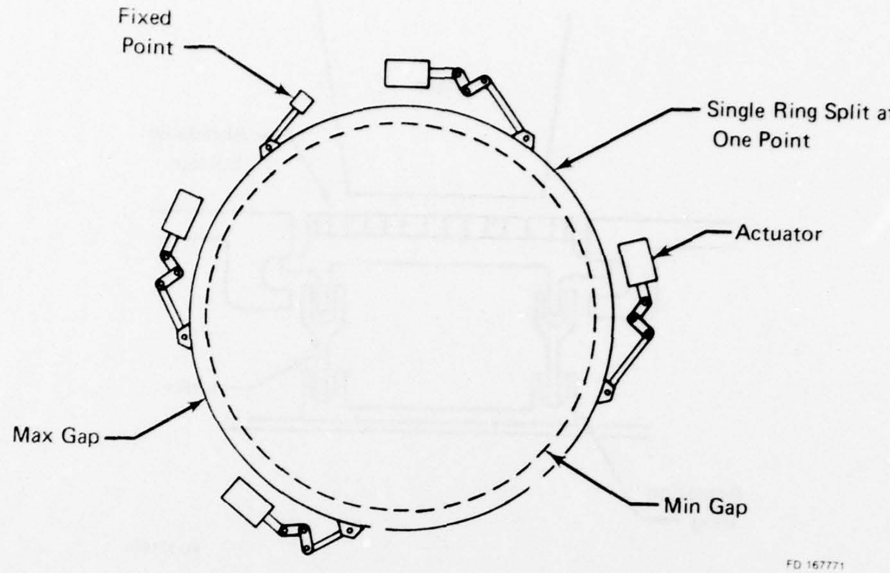


Figure 18. Scheme No. 14, Split Hoop Variable Shroud, Multiple Actuation

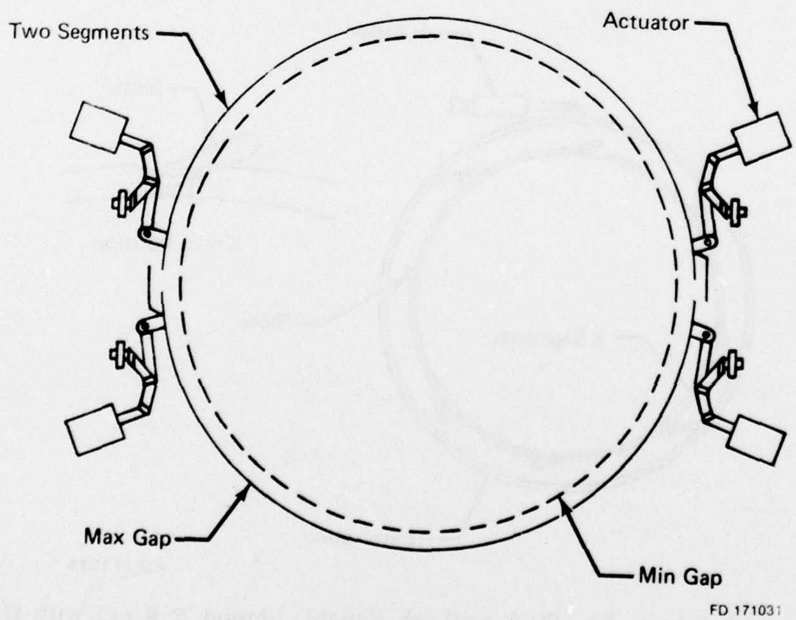


Figure 19. Scheme No. 15, Split Hoop Variable Shroud, Two Sections

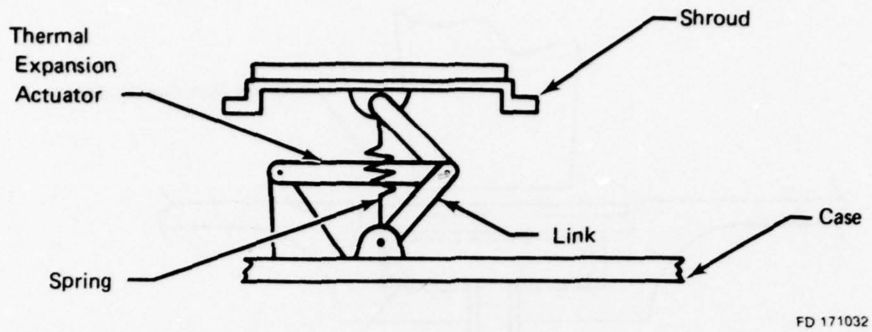


Figure 20. Scheme No. 16, Thermal Link Actuated Shroud

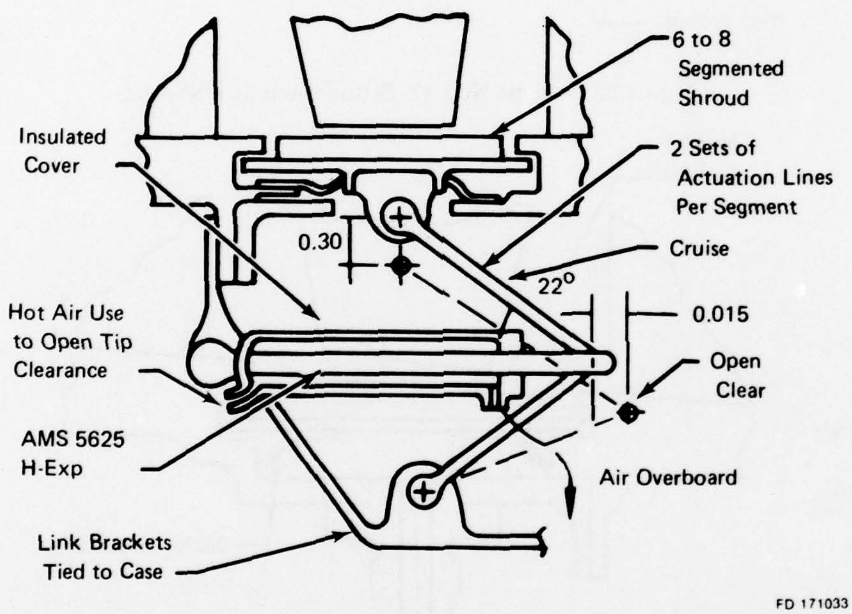


Figure 21. Scheme No. 16A, Thermal Link Actuated Shroud, Improved

Scheme No. 17. Metallic Bellows. Pressurizing the bellows causes the shroud to deflect inward to reduce clearances (see Figure 22). Reducing the pressure allows gas path pressure to force shrouds outward, opening the clearances.

This scheme requires segmented shrouds. Continuous shrouds would require large loads and have only small allowable deflections due to buckling limits. This scheme is not applicable to those compressors which require continuous shrouds. Fatigue and rub wear of the bellows may also cause problems. It would not be easily modulated due to controls and feedback problems, but would be easier to use with two-position operation where case stops would locate the shrouds. The required pressure must be air supplied as no fuel is permitted where leakage could cause fuel to flow into the gas path (see Figure 23). Additional high pressure pumping is then required.

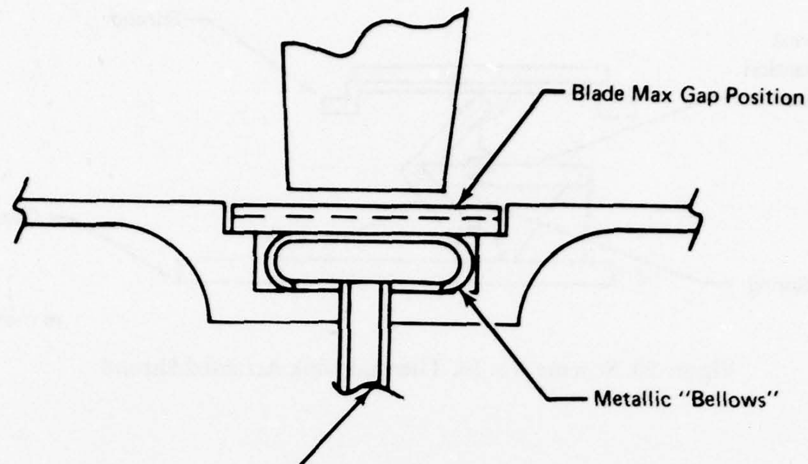


Figure 22. Scheme No.l 17, Bellows Actuated Shroud

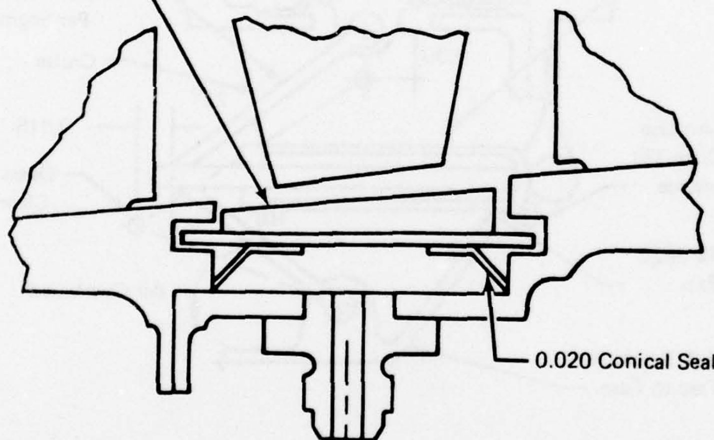


Figure 23. Scheme No. 17A, Pneumatic Actuated Shroud

The scheme does have a fast response and is mechanically simple. It controls blade tip and not stator clearance, however, and has potential design and manufacturing problems where the pressure feed tubes enter the bellows causing a weak and fatigue-prone joint.

Scheme No. 18. Bellows Actuated Stator Group. Scheme No. 18 is similar to No. 17, but the shrouds are tied to the stators providing control on both stator and rotor clearances (see Figure 24). The stators are segmented to eliminate hoop loads.

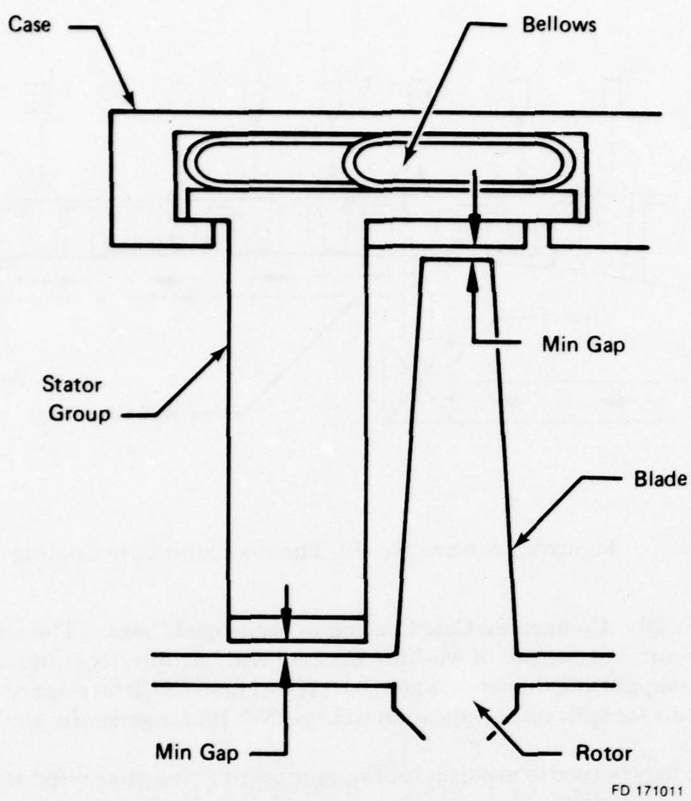


Figure 24. Scheme No. 18, Bellows Actuated Shroud and Stator Group

The actuation system must account for a moment at the root caused by stator blow off load. This would require a wide flange to distribute the load, and additional actuation force to overcome the friction due to this moment. Tip leakages would increase due to segmented stator group end seals, and stator shrouds are less effective structurally because of the segmenting. It is not a positive return type and would be prone to sticking on return due to friction.

Thermal Case Cooling/Heating. Schemes No. 19 through 22. These schemes all operate by heating or cooling the structural case with air. The schemes are mechanically simple, have few moving parts (a valve), little parasitic leakage, and positive response. Their principle drawbacks are slow response, limited magnitude of clearance control, and not being able to set stage clearances independently from neighboring stages. Some modulation is possible by controlling the amount of air flow or by mixing hot and cold air.

Scheme No. 19. Compressor Case Cooling — Split Cases. This scheme cools the rear compressor stages by washing fan duct air along the cases (see Figure 25). It only works for rear stages where $T_{core} - T_{fan}$ is large enough. This particular scheme is designed for split case compressors where circumferential bolt rings are absent. The presence of such rings will reduce cooling effectiveness.

Clearance closedown will change from front to back as the temperature driver changes. The system needs to be activated at all times during cruise and therefore has a continuous performance penalty during operation. Good position and leakage control is possible and recirculation seals are eliminated. There are no mechanical fitting problems as with mechanical systems. The scheme may only be feasible with cantilevered stators or stators with segmented ring shrouds since shroud compressive loads can exceed stator buckling loads.

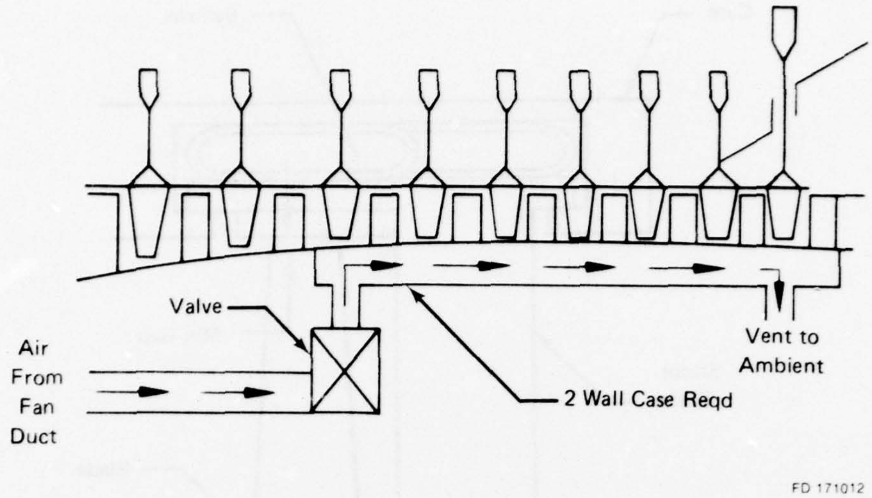


Figure 25. Scheme No. 19, Thermal, Split Case Cooling

Scheme No. 20. Compressor Case Cooling — Segmented Cases. This scheme also cools the cases with duct air, but instead of washing the case with air directly it impinges the air on the structural rings supporting the shrouds and stators (see Figure 26). It is designed for segmented cases but the comments for split case application (scheme No. 19) are generally applicable.

Insulation may be used to make the case and supporting ring more responsive to cooling air by reducing the film coefficients (heat transfer) on the core air side. This concept can be used on other case cooling/heating schemes to improve the sensitivity of case temperatures to a given amount of cooling air. This would, of course, make the scheme more efficient.

Scheme No. 21. Thermal Case Heating/Cooling. This scheme selects either heating (SLTO) or cooling (cruise) depending on the clearance change required (see Figure 27). A greater range of control is possible because of the additional clearance change generated by both heating and cooling the shrouds rather than just cooling as provided by schemes No. 19 and 20. Figure 28 shows scheme No. 21A Thermal Segmented Case Heating and Cooling.

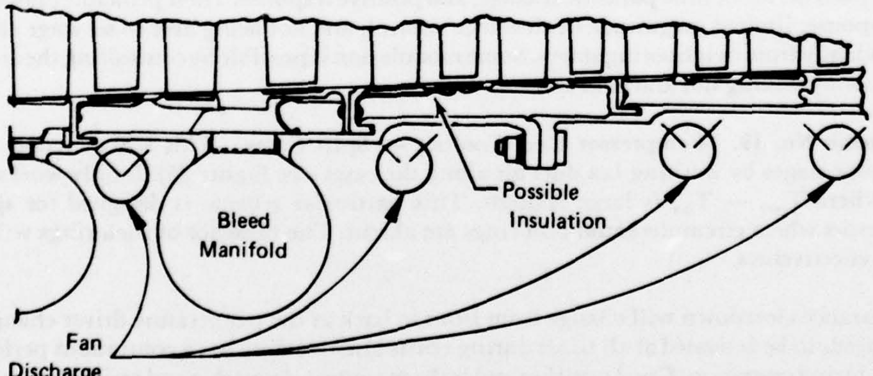


Figure 26. Scheme No. 20, Thermal, Segmented Case Cooling

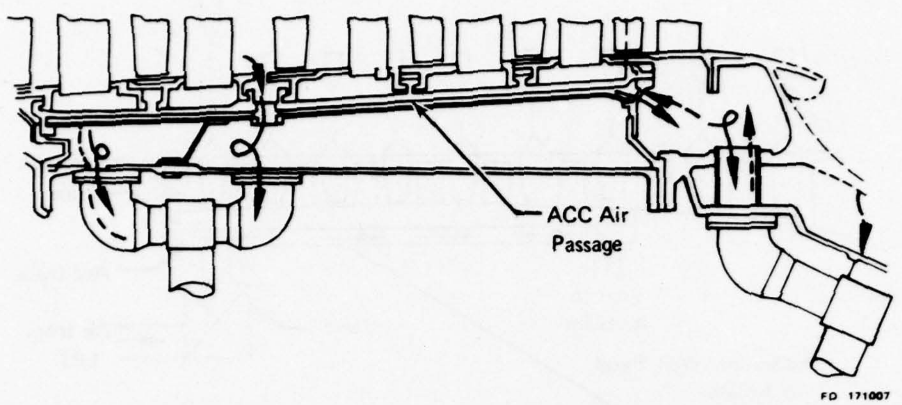


Figure 27. Scheme No. 21, Thermal, Split Case Heating and Cooling

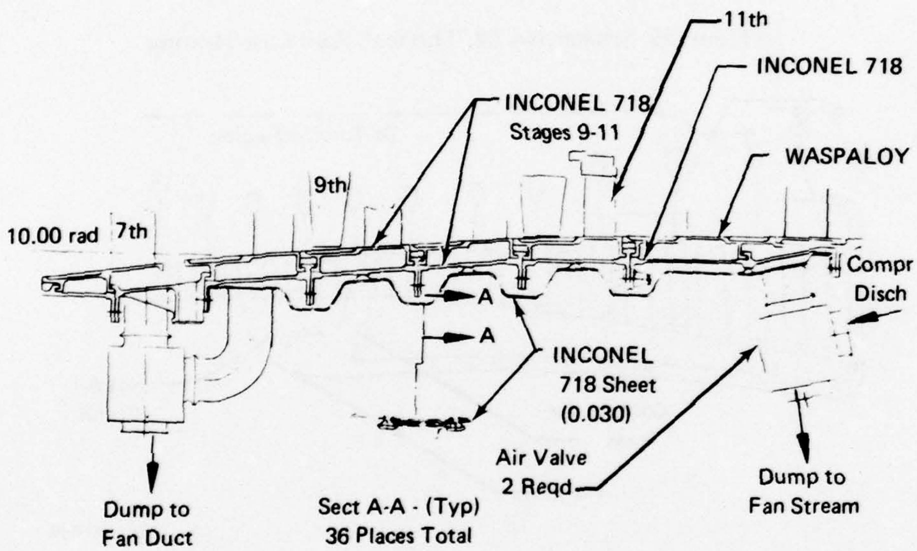


Figure 28. Scheme No. 21A, Thermal, Segmented Case Heating

Scheme No. 22. Thermal Case Heating. This scheme uses LPT air to heat the compressor cases during potential rub situations maintaining the cases away and avoiding a rub (see Figure 29). The system is only activated during deceleration and therefore incurs no performance penalty during cruise. The minimum clearance is with the control off; therefore minimum operating clearances are set by build clearances. This may limit operating clearances.

Schemes No. 23 and 24. Bore Heating and Cooling. These schemes bleed mid stage compressor air and cool or heat the compressor disk bores to control disk diameter and blade tip gap (see Figures 30 and 31). They do not offer a large range of control and have major structural problems caused by cooling the disks while still having rims at the adjacent gas path temperature. The resulting bore to rim gradients severely limit low cycle fatigue (LCF) life. Heating the bores is equally unsatisfactory because creep life is limited at the normally elevated temperatures at which the disks operate.

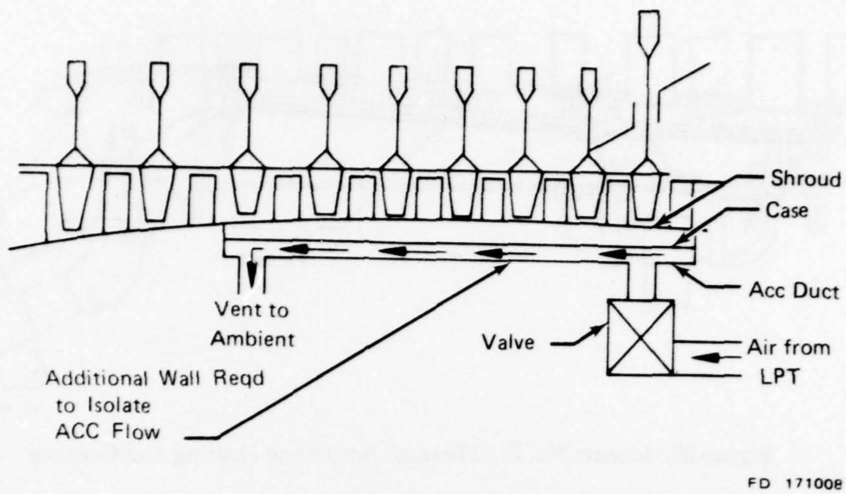


Figure 29. Scheme No. 22, Thermal, Split Case Heating

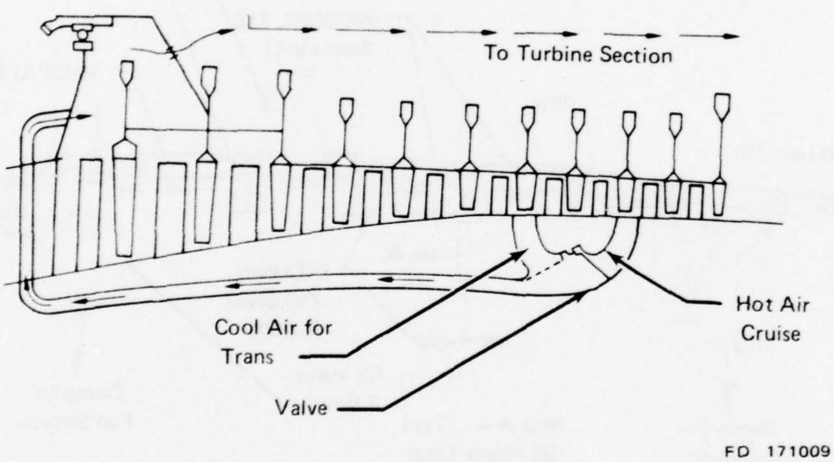


Figure 30. Scheme No. 23, Thermal, Bore Heating and Cooling

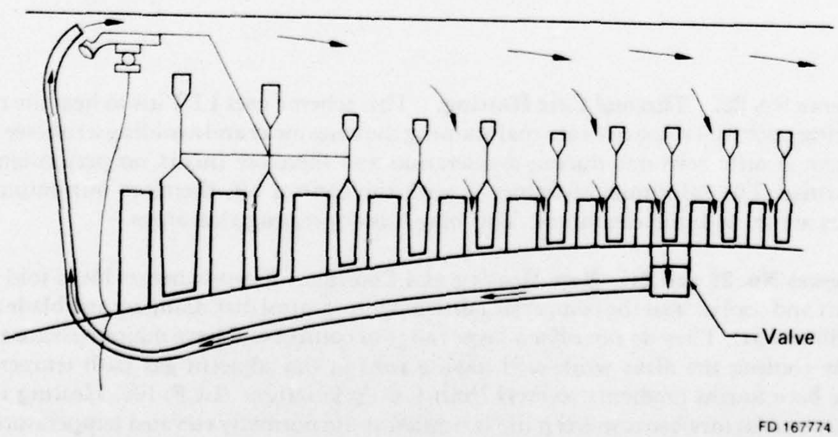


Figure 31. Scheme No. 24, Thermal, Bore/Rim Heating

Scheme No. 25. Floating Vane and Case. This is a passive scheme(Figure 32) where the blade tip shrouds are isolated from case ovalization by tying them directly to the bearing compartment support. It was included to demonstrate that a combination of active and passive systems might be used, each to treat a different clearance limiting mechanism.

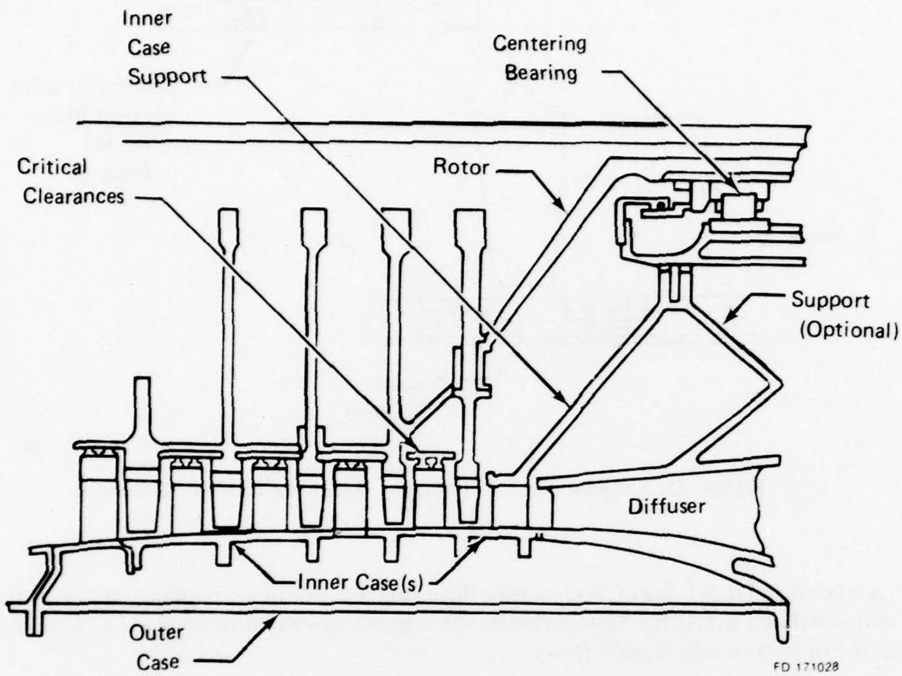


Figure 32. Scheme No. 25, Floating Vane and Case

Scheme No 26. Thermal-Electrically Heated Shroud. This thermal scheme uses a ring shroud with imbedded electrical heaters (Figure 33). The heating elements are activated during expected pinch points and heat the shrouds, causing them to expand and increase clearances. The system would be turned off (or operated at low power) during cruise to allow clearances to close. Power consumption would be principally during transients with only a low level required during steady state. There is no electrical power supply available to meet these requirements and development would be a high risk. In addition, electrical heating rods are unsuitable for the already material temperature limited turbine or the rear stages of the compressor. Allowable heating rod temperature and maximum allowable shroud metal temperature will determine how effective the heating rod scheme is.

Use of electrical systems that are integral with major cases have a poor reliability history. Sealing from moisture is a major problem when fastner and plug are manufactured as a part of the case. Potential vibration and shock breakage of wires results in low system reliability. The system is mechanically simple, has few parts, no moving parts and provides good clearance control. Small manufacturing tolerance build-up, with potentially faster response than case air heating and cooling schemes is possible, but is probably not as fast as mechanical schemes.

Schemes No. 27 through 30 are applications of schemes similar to 26, 17, 7, and 6A, to the compressor exit seal. Consideration of ACC is given to the seal because of the large pressure drop and significant flow of expensive air passing through it. Evaluation of the benefits of ACC on this seal gives a representative indication of the potential benefit of ACC on primary engine seals other than main gas path seals.

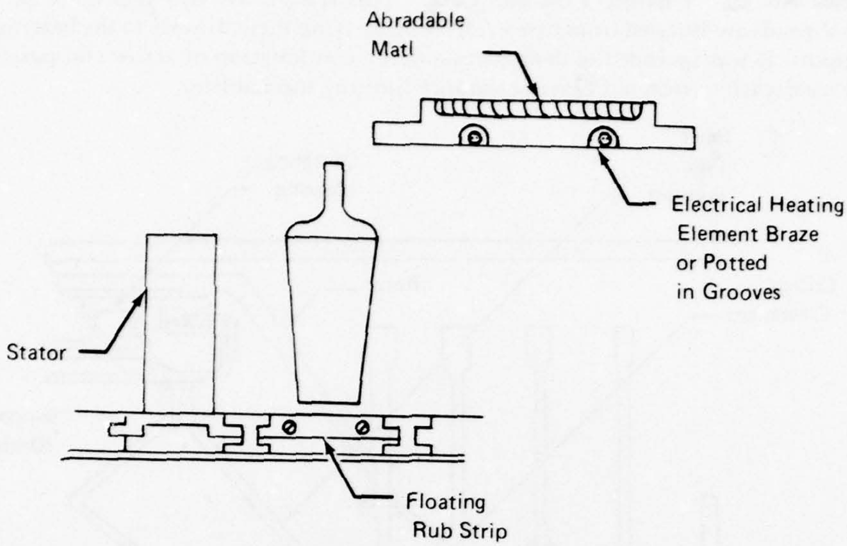


Figure 33. Scheme No. 26, Thermal, Electrically Heated Shroud

It is recognized that it may not always be desirable to have the seal operate as closed as possible, since thrust balance and other system needs may require specific flow level. ACC would, however, provide the option to adjust such flows.

Scheme No. 27. Rear Compressor Seal — Electrical/Thermal. Large temperature changes are required to generate small clearance changes (30°F per 0.001 in. approximately) with an ambient environment up to 1100°R, 0.02 in. clearance closedown would require the seal backing to be at 1700°R; this may not be practical (see Figure 34).

Note that the relative radial positions of knife edges and the land would have to be reversed from that shown in the picture to allow land thermal growth to close clearances. The knife edge and land supports would then have to be overhung to allow the knife edges to be supported on the rotor if heating the shrouds is used to open the clearance. Alternately, the KE seals could be set tight at assembly. Heating the shrouds would then open the clearance without overhanging the supports.

Scheme No. 28. Bellows Type Seal — See Scheme No. 17. This scheme is similar to scheme No. 17, but is applied to the rear compressor seal (see Figure 35). The bellows must operate under load at 1200°R for rear compressor or turbine stages. This is beyond the limit of present materials used as springs. The scheme also requires an additional high pressure pump or careful pressure balancing to allow activation while preventing axial cocking due to front-to-back pressure gradient.

Labyrinth seals are generally located at smaller diameters, thus ring seals are stiffer than tip shrouds and may require ring segmentation.

Scheme No. 29. Rear Compressor Strap Seal. This scheme is similar to scheme No. 7 but is applied to the rear compressor seal (Figure 36). It requires pressure balancing which may not be possible at all operating conditions. The effects of extra leak passages, recirculating air, and leakages through the required slots in the ring must be accounted for.

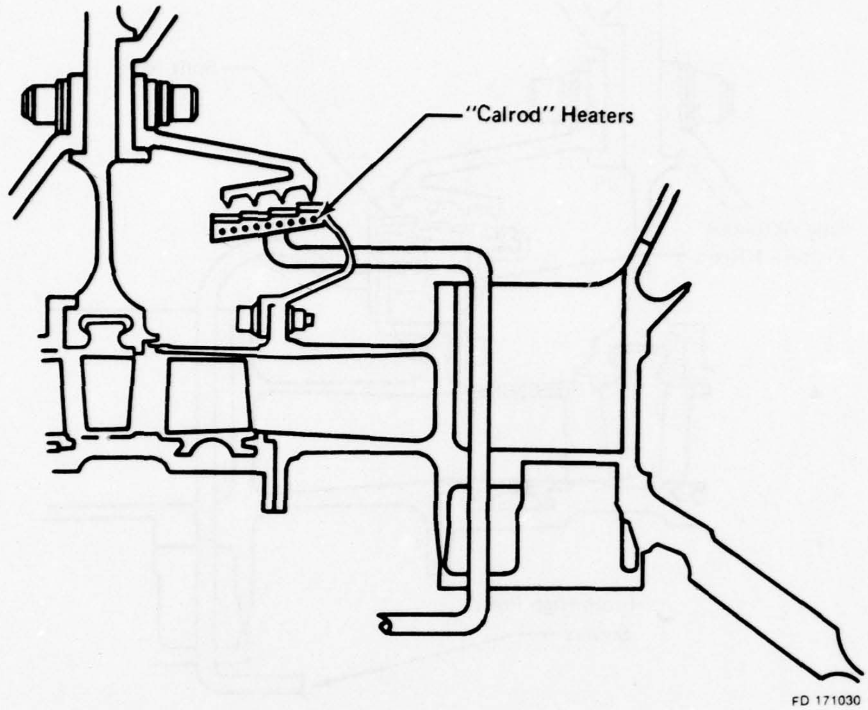


Figure 34. Scheme No. 27, Thermal, Electrically Heated Rear Compressor Seal

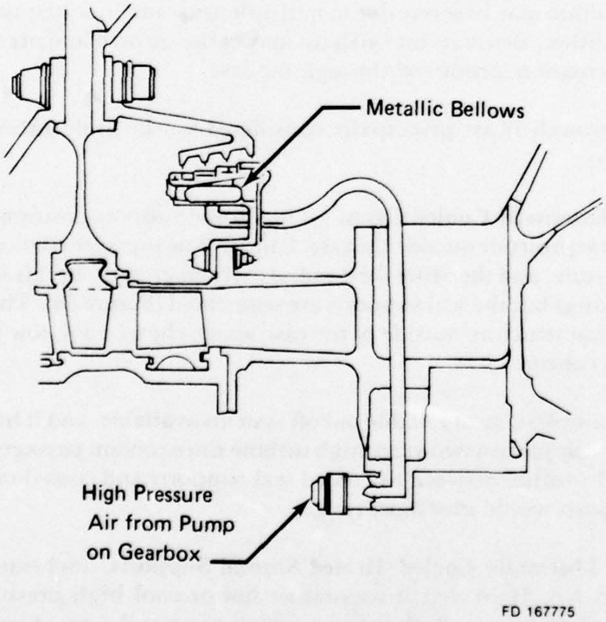


Figure 35. Scheme No. 28, Rear Compressor Seal, Bellows Acutuated

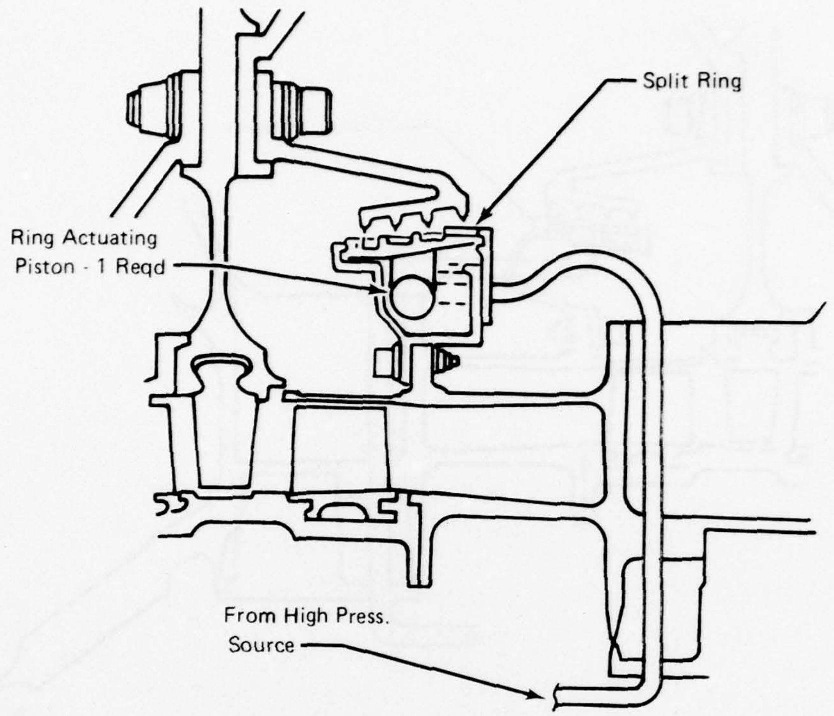


Figure 36. Scheme No. 29, Rear Compressor Seal, Pneumatic Band Actuated

Scheme No. 30. Rear Compressor Seal — Mechanically Actuated Ramp. This scheme (Figure 37) is similar to scheme No. 6A. It has a long linkage path making seal accessibility a problem. Tolerance buildup may be severe due to multiple arms and links required for access to the remote location. In addition, thermals on linkages may cause growth and accuracy problems, as well as the sealing of actuation torque rod through the case.

Schemes No. 31 through 38 are principally considered for the high turbine because of high temperature adaptability.

Scheme No. 31. Externally Cooled Cases. The shroud support positions are controlled by rails and bolt flanges that protrude outside the case. Fan air (low pressure) is blown onto these rails to control their temperature, and therefore their radial thermal growth. In this scheme the shrouds and rails are complete rings but the seal supports are segmented (Figure 38). The design moves the principal shroud location structure outside of the case where cheap, cool, low pressure air can be used to affect clearance control.

This is one of the simplest, most reliable on/off systems available, and it has undergone some optimization. It is easy to apply to a two-stage high turbine since coolant passages are external to the case, and the structural conflict between uncooled seal supports and cooled rail limits clearance range. Segmented supports would give more range.

Scheme No. 32. Thermally Cooled/Heated Shroud Supports. Scheme No. 32 is a more advanced concept than No. 31 in that it uses either hot or cool high pressure compressor air depending upon desired clearances. Both the shroud supports and cases (Figure 39) are directly cooled eliminating the thermal structural conflict of scheme No. 31, while making the clearance change more responsive to cooling air. The system should have a greater range of clearance control

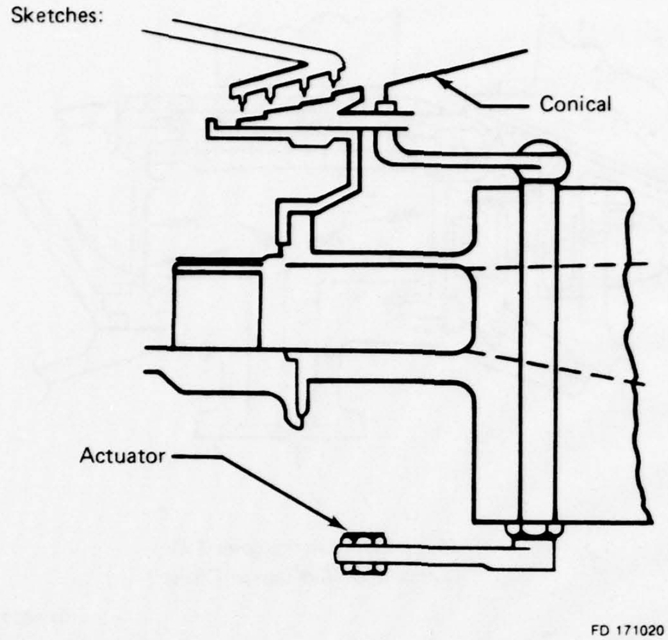


Figure 37. Scheme No. 30, Rear Compressor Seal, Mechanical Link Actuated

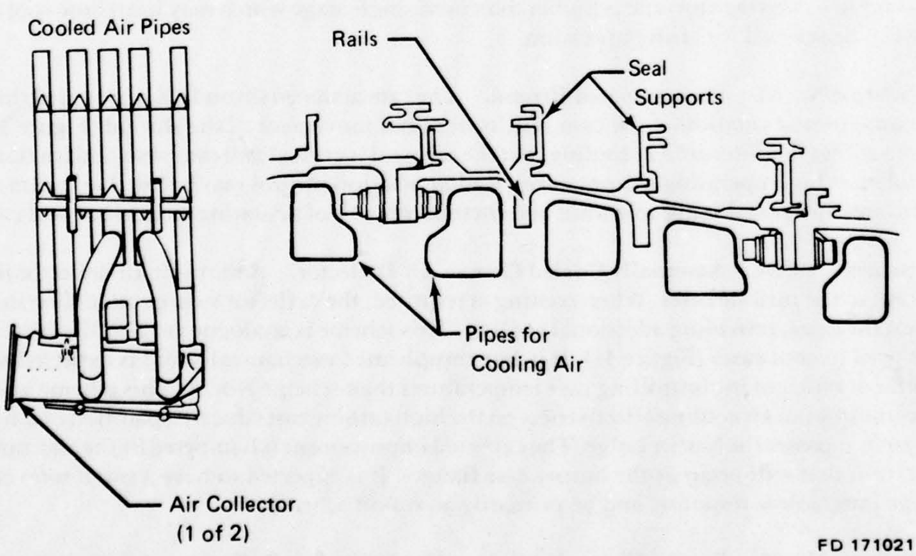


Figure 38. Scheme No. 31, Thermal, Externally Cooled Cases

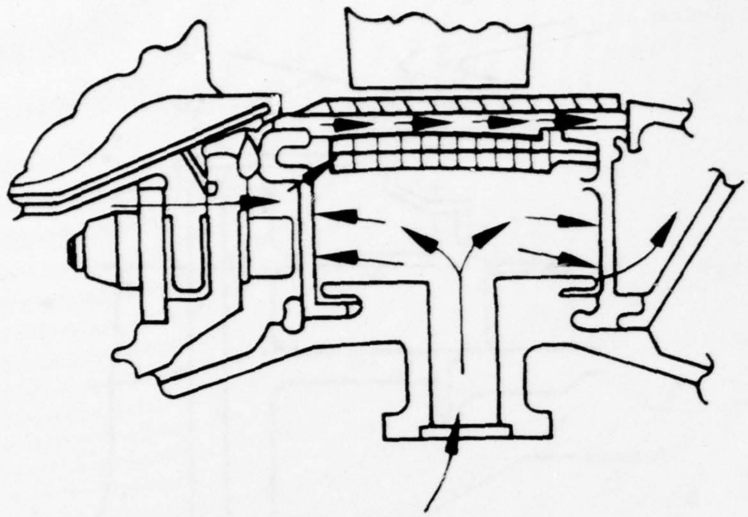


Figure 39. Scheme No. 32, Thermal, Cooled/Heated Shroud Supports

than scheme No. 31, but at a higher risk and greater weight due to the heavier piping and beefier valves required of high pressure system. It further combines case and shroud cooling air supply with ACC. High pressure air is not wasted after ACC use. It is more easily adapted to single stage high pressure turbine. In a two stage high turbine, the second stage shroud and vane C/A must be routed past the first stage ACC resulting in some possible design problems. Also, dump pressure behind the first stage of a two stage turbine is higher than for a single stage which may limit how cool a supply stage can be selected for cruise operation.

Scheme No. 33. Cam Actuated Shroud. The cam actuated shroud rides in angled slots where a circumferential rotation of the cam results in radial movement of the shroud (Figure 40). This scheme allows for outer air seal cooling, but the case seal is critical and cam wear and friction may be a problem at high operating temperatures. Radial position control may be lost due to cam and ring machining and positioning tolerance and thermal growth of actuating ring, slots, and cams.

Scheme No. 34. Externally Cooled Case — Air Deflector. A movable air deflector is located adjacent to the turbine cases. When cooling is required, the deflector swings out deflecting fan air against the cases, providing additional cooling. This scheme is analogous to No. 31 in that fan duct air is used to cool cases (Figure 41). It is less complicated mechanically and is expected to be less effective or efficient in controlling case temperatures than scheme No. 31. This scheme attempts to overcome low fan air cooling effectiveness on the high turbine cases due to separation of fan air from the case as it passes the burner bulge. The expected improvement is hampered by the additional flow separation that will occur at the burner case flanges. It is expected to have a small total clearance change range, slow response, and be primarily an on-off scheme.

Scheme No. 35. Externally Cooled Case — Insulation/Air Deflector. Insulation is mounted to swing away from the case diverting fan air onto the case when cooling is required, or be clasped tightly against the case, insulating it from the fan air when a hotter structure (larger clearances) is required (Figure 42). In the cooling position it acts similar to the flow deflectors of scheme No. 34, but in the "hot" position the deflectors provide additional insulation. This is expected to result in

greater case response range than scheme No. 34. Areas of concern include long term stability of installation and linkage dependability. The possiblity of fan duct air blockage during cruise (insulation away from walls) may cause large parasitic losses in the fan duct which must be bookkept as a loss. The build tolerance is not critical, but a complex linkage and sync ring are required for the two-stage turbine case with flanges.

Scheme No. 36. Blade Tip Erosion Compensator. This scheme (Figure 43) is a hybrid between an active and a passive scheme. It points out the need to consider long term deterioration mechanisms and ACC devices to compensate for it. It may be feasible and beneficial to include or allow for such compensation in proposed schemes. Items of concern are (1) shroud angles changes will create a trailing edge, (2) discontinuity in the outer wall may cause a loss in performance and (3) an invention is required to "fold" part of the tip shroud inward to compensate for erosion but still provide for shroud cooling.

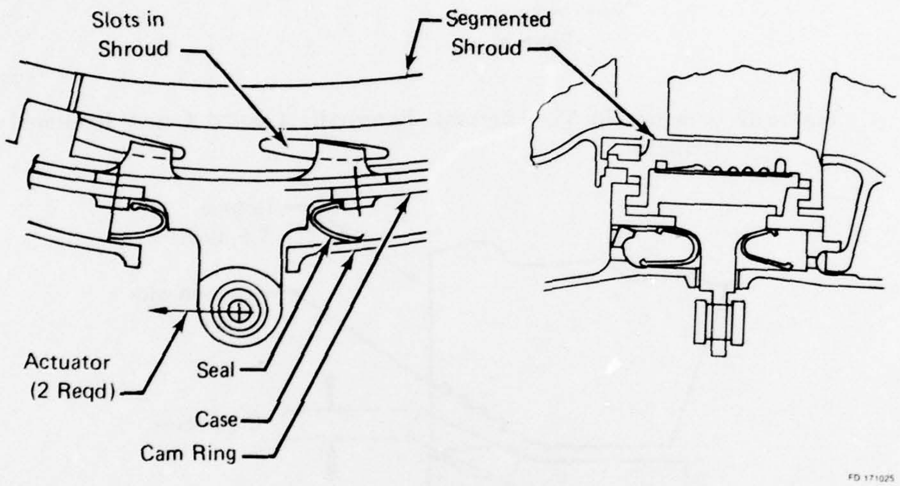


Figure 40. Scheme No. 33, Cam Actuated Shroud

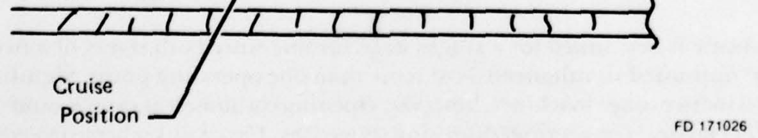


Figure 41. Scheme No. 34, Thermal, Externally Cooled Cases, Air Deflector

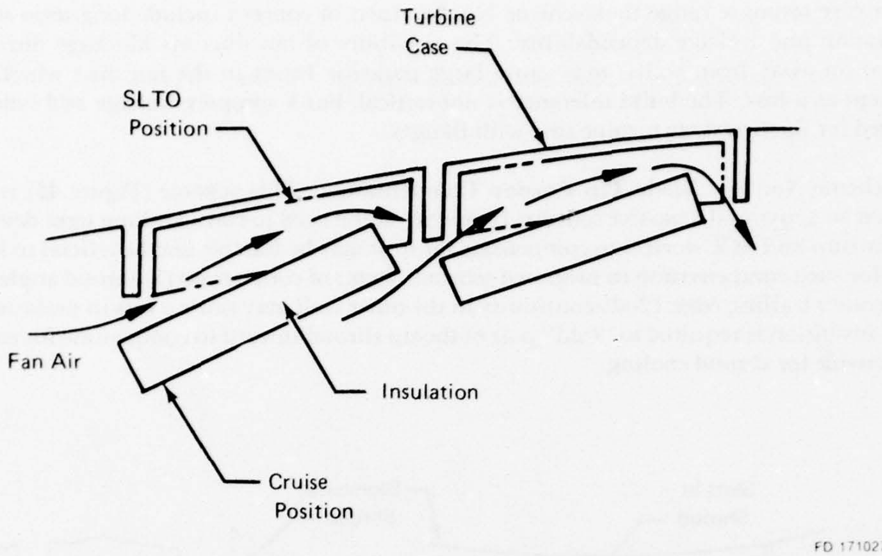


Figure 42. Scheme No 35, Thermal, Externally Cooled Cases, Insulated Air Deflector

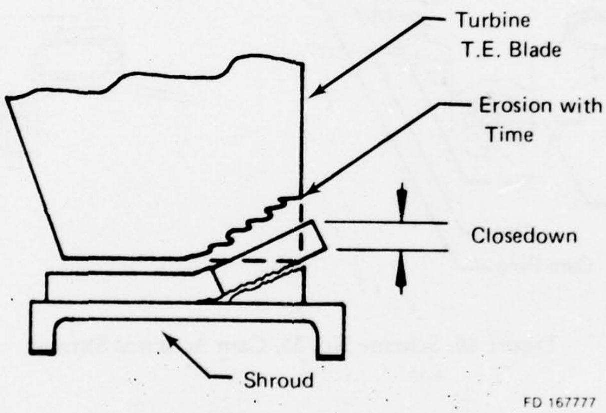


Figure 43. Scheme No. 36, Blade Tip Erosion Compensator

Scheme No. 37. Rotor Shift, Conical Shroud. This is similar to schemes No. 3, 4 and 5. This scheme may be more desirable for turbine ACC than compressor ACC due to the naturally diverging flowpath and potentially large angles (Figure 44). Mechanical difficulties are similar to schemes No. 3, 4 and 5 with the modification that larger angles mean less axial shift. Turbine ACC is naturally more difficult due to the severe thermal environment and need of cooling, which makes this scheme relatively more favorable for turbine applications since it requires no changes to case cooling or structure.

This scheme is best suited for a single stage turbine since both stages of a two-stage machine could not be optimized simultaneously at more than one operating point. Significant benefits are still expected for two-stage machines, however. Opening turbine clearances would close compressor clearances for classical converging/diverging flowpaths. Use of this scheme may then require ACC on the front of the compressor (where flowpath angles are relatively large) to counteract this effect.

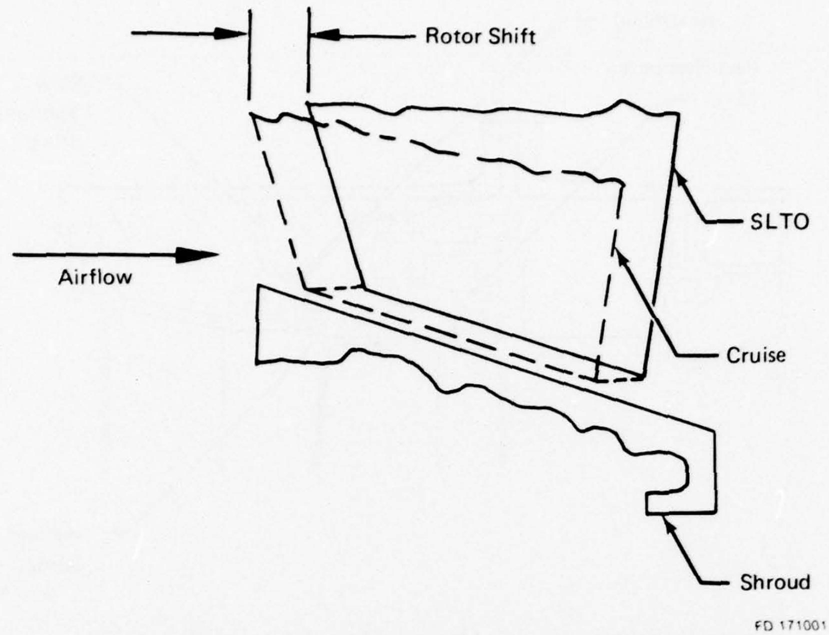


Figure 44. Scheme No. 37, Axial Rotor Shift, Conical Shroud

The engine length increases due to compressor rotor/stator axial clearance requirements as well as turbine axial clearance. The scheme has the same PTO bevel gear problem as scheme No. 3. The scheme will also affect the rim cavity seals by opening the gap axially. In addition, the thrust bearing is far away from the turbine, hence axial motion due to thermals will be large. Turbine tip clearance control will be more difficult to maintain by shifting the rotor due to thermal generated axial position changes.

Scheme No. 38. Fast Thermal Response Shroud Ring. This scheme combines active and passive clearance control, and is based on a Rolls-Royce patented passive control system. In the passive mode it provides clearance control by keeping the shroud away from the blade during acceleration and deceleration pinches. This is accomplished by tailoring the thermal time response of the controlling structures. The key feature of the scheme is that the structure is designed to provide control in the direction of opening clearances only. During the deceleration pinch the blade cools and RPM's drop quickly, hence opening clearances. The case then cools causing the pinch, and finally the disk cools opening the clearance again. The "slow response ring" has a response tailored to the disk response, and holds the shroud away from the blades when they would normally be closed down by case shrinkage, therefore preventing a rub (see Figure 45).

The "fast response ring" has a separate cooling air feed and is drilled with air passages for faster time response. During the acceleration pinch the clearances normally close when the case controlled shrouds do not respond as fast as the blade-disk. With this scheme, however, the shrouds are uncoupled from the cases on acceleration only and are pulled away quickly by the fast response ring.

This scheme relies on being able to tailor the time responses of the various shroud controlling rings to the time response of the rotor and blade. It must be demonstrated that the fast response ring can be made to respond at the required rate of 100°F/sec.

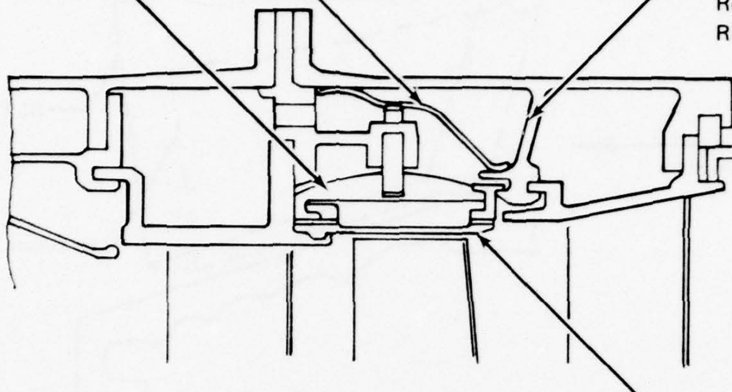


Figure 45. Scheme No. 38, Thermal-Heated/Cooled Shroud, Passive

Scheme No. 38A. ACC Fast Thermal Response Shroud Ring — See Scheme 38. This scheme is a true ACC idea prompted by the assumption that a shroud controlling ring can indeed be made to respond at the rate of 100° F/Sec (required of scheme No. 38) and supply enough force to displace the shroud (see Figure 46).

In this scheme the shroud location is controlled by such a ring, but the ring cooling air is now modulated by mixing air from two different compressor stages to provide ACC.

This scheme is fundamentally different from other thermal schemes in that it provides a fast response capable of tracking transient clearance changes. It has to be demonstrated, however, that such a fast response ring can be designed.

The scheme promises good control, high reliability, low purchase and development cost. If it could be made to work it would be a prime scheme.

- Shroud cooling air part of ACC air
- ACC air dumped into flowpath aft of blade
- Two-stage turbine needs to separate vane cooling air from ACC air required.

Scheme No. 39. Thermally Heated/Cooled Shrouds/Case. This scheme is analogous to scheme No. 32 in that it uses two different stages of high compressor air to heat/cool the low turbine cases. The scheme requires an annular gap in the cases to carry the cooling air from stage to stage, then dumps this high pressure air into the main gas path after flowing through cooling passages in the case structure (see Figure 47).

- More advanced concept than blowing air on OD of case
- Should have better range of control than blowing air on case OD
- Higher risk and greater weight due to high pressure plumbing and air control valve

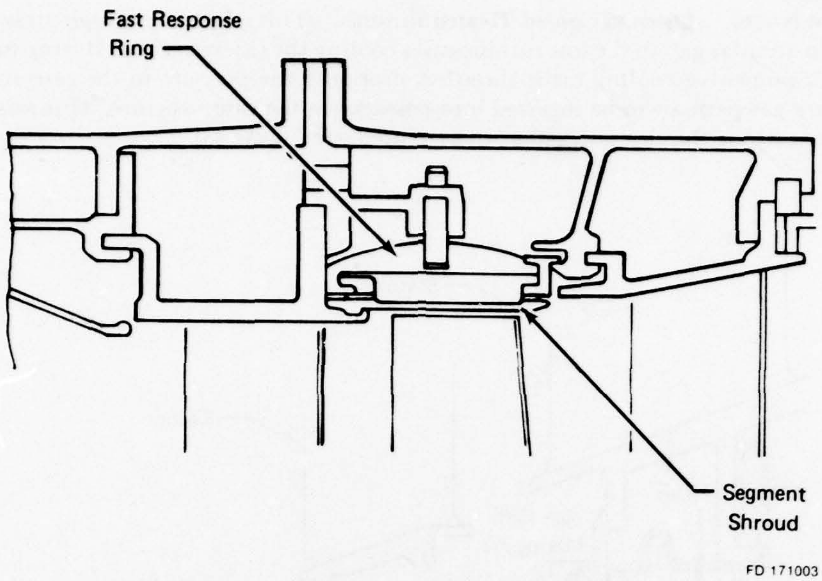


Figure 46. Scheme No. 38A, Thermal-Heated/Cooled Shroud Active

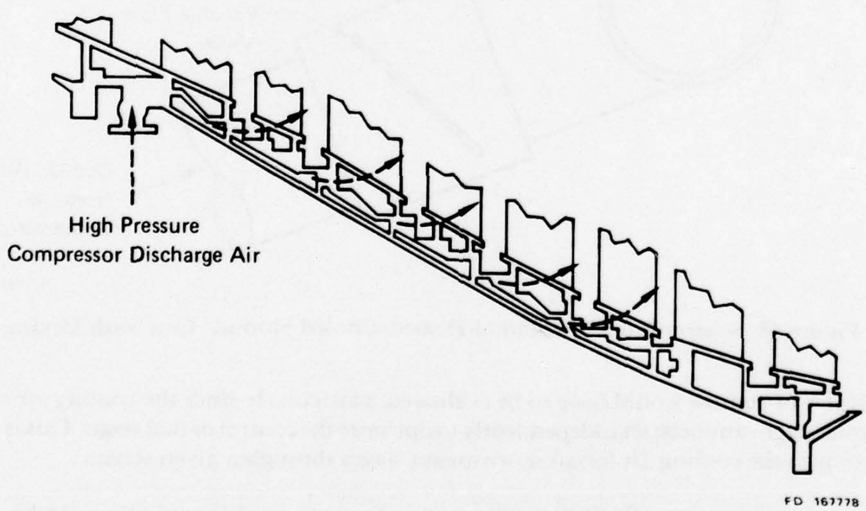


Figure 47. Scheme No. 39, Thermal-Heated/Cooled Shroud Case

Scheme No. 40. Thermal Cooled/Heated Shrouds. This scheme feeds high pressure cooling air along an annular gap in the low turbine cases cooling the cases at cruise. During transients or other pinch points the cooling air is throttled, dropping the pressure in the case annulus and allowing hot gas path air to be ingested into passages in the case structure. This raises the case temperature causing the clearances to open as desired (see Figure 48).

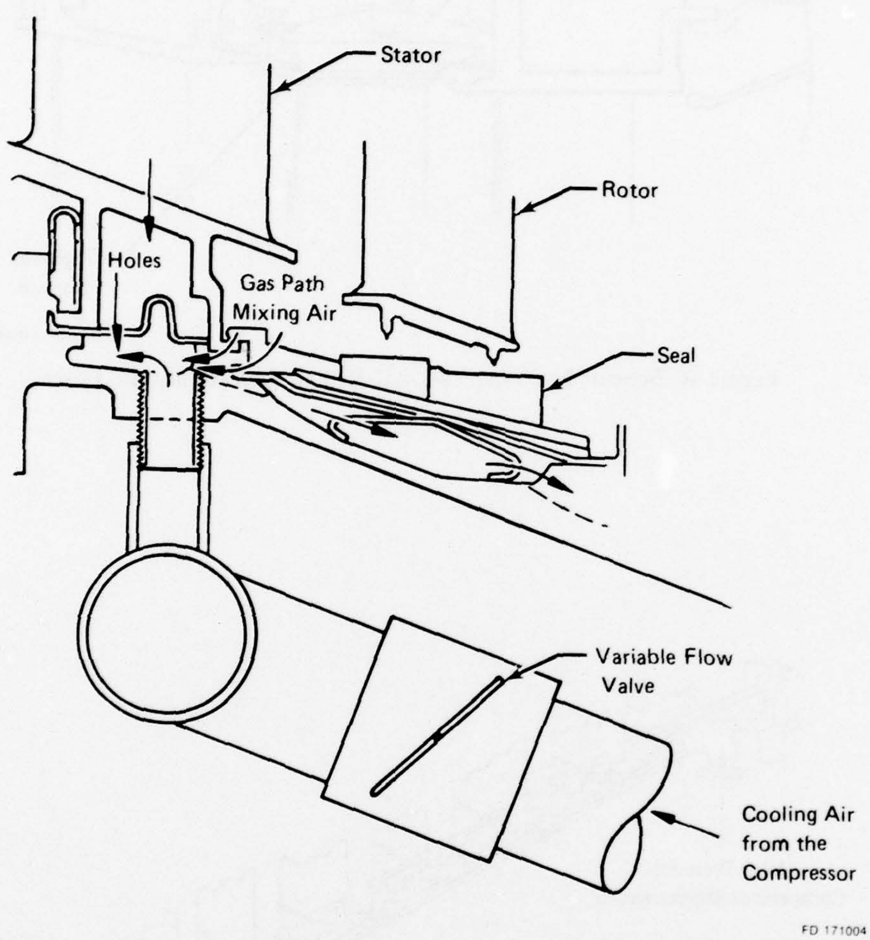


Figure 48. Scheme No. 40, Thermal-Heated/Cooled Shroud/ Case with Mixing

The degree of control would have to be evaluated, particularly since the cooling air requirements for each stage cannot be set independently to optimize the control of that stage. This is a result of having to pass the cooling air for all downstream stages through a given stage.

The accuracy in setting the back pressure in order to control ingestion would have to be evaluated to determine if a fine enough control can be built.

Scheme No. 41. Vane Air Cooled Shrouds and Case. This scheme is analogous to scheme No. 40, but regulates the C/A dump rather than supply pressure. It uses vane cooling air for both case cooling and ACC, which leads to potential temperature and flow volume compatibility problems (see Figure 49).

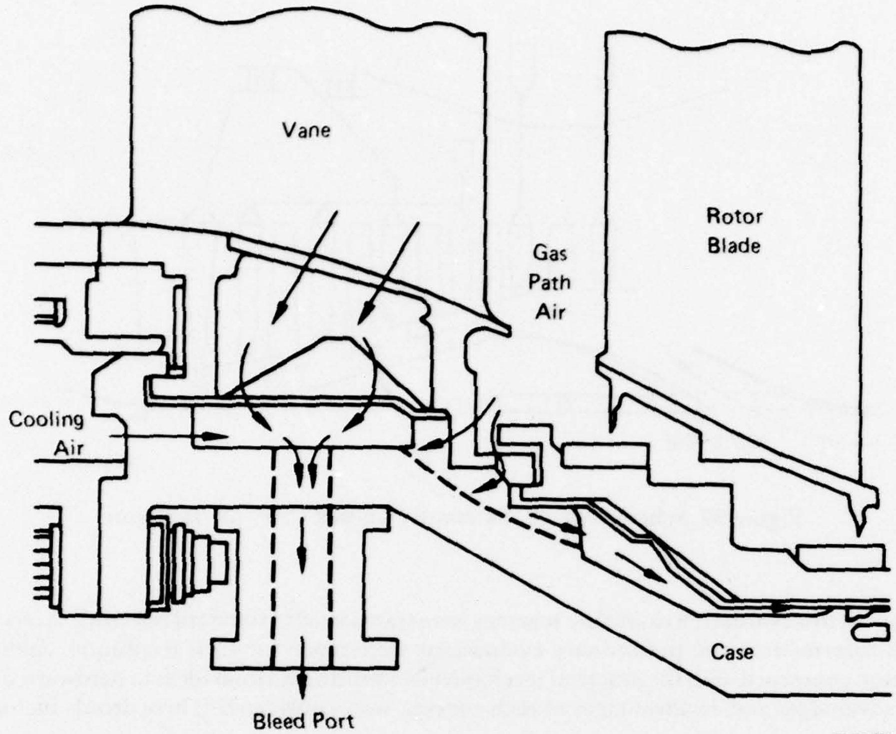


Figure 49. Scheme No. 41, Thermal-Heated/Cooled Shroud Case with Vane Bleed

The scheme has the disadvantage over scheme No. 40 that cooling air is wasted when seals need to be opened (open bleed part). For this reason scheme No. 41 may be superior.

Scheme No. 42. Externally Cooled Case. This scheme functions similar to No. 34 but provides a captive path for the redirected fan air flow. This should improve the separation problem, but adds weight and cost. The same advantage and disadvantages apply as for scheme No. 34 otherwise (see Figure 50).

- Low range of clearance change
- Slow response
- Primarily on-off control (2 position).

2.1.3 Culling of Schemes

The extensive list of schemes uncovered contained both patently unworkable schemes, and groups of schemes with only minor differences. By combining similar schemes and eliminating unworkable schemes according to the following guidelines, the number of schemes to be considered in detail was reduced.

- Techniques that were variations on a scheme were evaluated with respect to each other to determine if one variation was uniformly superior to others of the same type. In such cases the inferior schemes were dropped from further consideration.
- Schemes which had a fundamental flaw making them unworkable were dropped. An example of such a flaw would be a scheme which required material properties unrealistically beyond the limit of existing materials.

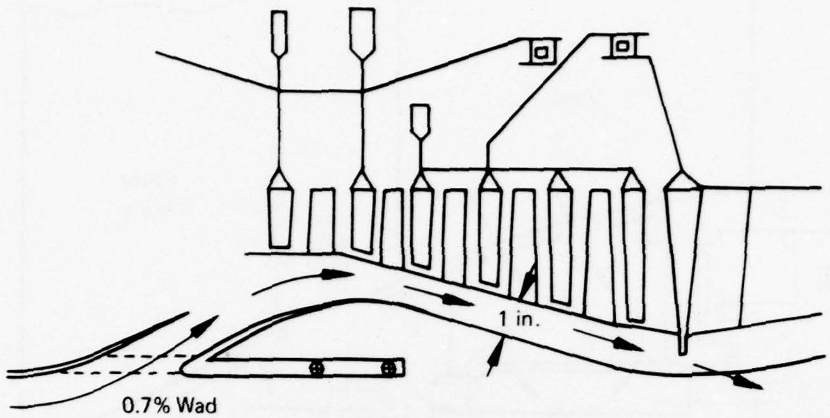


Figure 50. Scheme No. 42, Externally Cooled Case, Air Deflector

To aid in this evaluation candidate schemes were transferred to standard reference sheets where pertinent information and preliminary evaluations were made for each technique. Additional information concerned with the practical mechanics of adopting cartoon ideas to hardware, and the detailed advantages and disadvantages of each concept were considered. These details included:

- Sealing
- Adaptive hardware (arms, flanges, screws)
- Tolerances (machining, assembly)
- Actuation (link pins, unison rings, valves)
- Auxiliary equipment (pumps, pistons, generators, hydraulics)
- Power source
- Number of parts.

The scheme-by-scheme culling detailed in the following section resulted in reducing the total number of schemes to be considered from 51 to 16. This number was further reduced by consolidating schemes with considerably different appearance (generally because of application to different components) but based on the same operating principle. The scheme culling is illustrated in Figure 51 where a ladder showing the scheme combinations and final schemes is given. As a byproduct of the culling, a scheme application matrix, Table 3, was developed to summarize pertinent application information for each scheme. The component for which the scheme was considered, estimates of the response rate, types (levels) of control, range of control, and control actuation type are given to help characterize the schemes.

2.1.4 Description of Culling Procedure

Scheme No. 1A and 2. Cantilever Stator Tip Control. Schemes 1A and 2 were different applications of the same scheme and are generally similar to scheme No. 10. Scheme No. 10 was retained as representative of this type of scheme.

Scheme No. 3, 4, 5, 37, and 37A. Axial Rotor Shift Schemes. Schemes No. 3 and 5 operate on the same principle and provide the same benefit. Scheme No. 5, however, is mechanically simpler and has fewer moving parts. Scheme No. 3 was eliminated from further consideration with no loss in generality to the study.

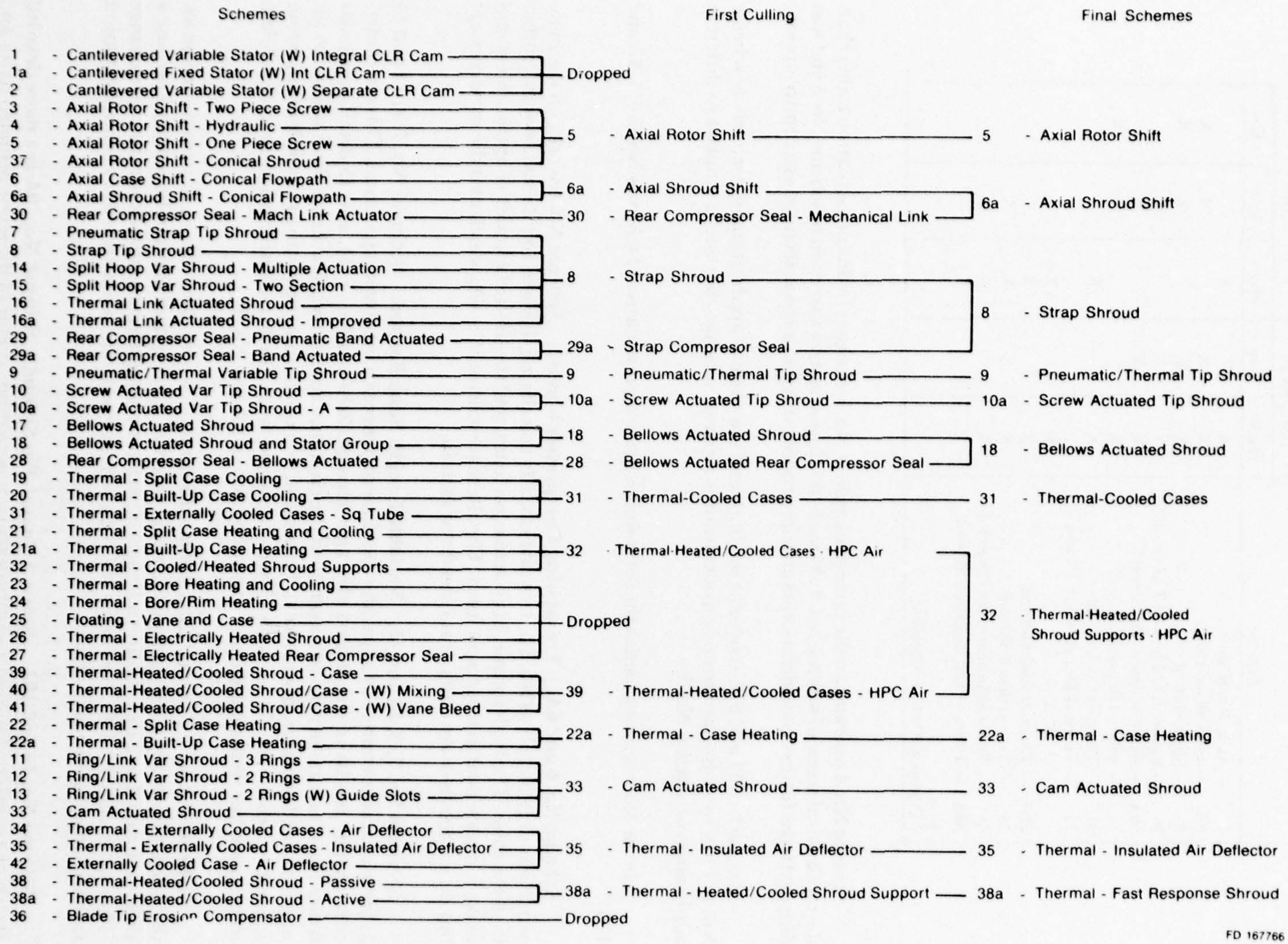


Figure 51. Scheme Culling Ladder

TABLE 3. ACC — SCHEME APPLICATION MATRIX

	Location				
	Compressor		Turbine		
Scheme	High	Low	High	Low	Seal
5 — Axial Rotor Shift	X		X		
6A — Axial Shroud Shift	X	X		X	X
8 — Strap Shroud	X	X		X	X
9 — Pneumatic/Thermal Tip Shroud	X	X		X	
10A — Screw Actuated Tip Shroud	X	X		X	
18 — Bellows Actuated Shroud	X				X
31 — Thermal Cooled Cases	X		X		
32 — Thermal-Heated/Cooled Cases — HPC Air	X		X	X	
22A — Thermal-Case Heating	X		X		
33 — Cam Actuated Shroud	X	X	X	X	
35 — Thermal-Insulated Air Deflector	X		X	X	
38A — Thermal Fast Response Shroud			X		

*Transport Only — Optional

Scheme No. 4 operates on the same principle as No. 5, but uses hydraulic actuation rather than the mechanical screw of scheme No. 5. As such, it is just a control variation of scheme No. 5 and was dropped from further consideration as an independent scheme, but was retained as a control option.

Scheme No. 37 and 37A represent the high and low turbine application respectively of scheme No. 5. They were dropped from consideration as separate schemes, but were retained as a different application of scheme No. 5.

Scheme No. 5 was retained as the rotor shift scheme representative of schemes No. 3, 4, 5, 37, and 37A.

Scheme No. 6 and 6A. Translating Compressor Shroud. Scheme No. 6 works on the same aerodynamic principle as No. 5 but involves axially translating the vane and shroud assembly rather than the rotor. The high torque, high actuation loads, and the limited number of applicable stages make it impractical in its present form. The alternate scheme, No. 6A, which uses the same concept but on a stage-by-stage basis, was considered instead.

Schemes No. 7, 8, 14 and 15. Variable Length Strap Shroud. Schemes No. 7, 8, 14 and 15 achieve clearance control by adjusting the circumference of a band or strap shroud. This circumference change results in the desired clearance change. Schemes No. 7, 14, and 15 detail particular hydraulic actuation devices to accomplish the clearance control, while scheme No. 8 uses an as yet undetermined actuator. Because all schemes function on the same operating principle of adjusting a band, schemes No. 7, 14, and 15 were dropped from further consideration as independent techniques, but were retained as a control option of scheme No. 8.

Scheme No. 16. Thermal Link Actuated Shroud. Scheme No. 16 is an actuation concept for the mechanically actuated segmented shroud schemes. This system may not be practical because a short actuator (1 to 2 in.) requires a large temperature change to get a significant clearance change (10 mils requires T = 500° F). Scheme 16A is an improvement that is considered as a control variation for mechanical shroud schemes.

Scheme No. 10 and 10A. Screw Actuated Tip Shroud. Scheme No. 10A is a more detailed sketch of a combined shroud and cantilever vane actuation scheme of the screw-actuated stator and tip shroud. It will be substituted for No. 10 (individually actuated shrouds); scheme No. 10 will be retained as an option if No. 10A proves unfeasible.

Schemes No. 11, 12, 13 and 33. Ring Link Actuated Shroud. Schemes No. 11, 12, 13 and 33 are variations on a mechanical ring-link control of segmented shrouds.

Scheme No. 12 is superior to No. 11 in that it requires one less ring while providing at least equivalent control. It is mechanically simpler and has less tolerance inaccuracy buildup. Of these two similar schemes, No. 12 was retained as representative of this class of scheme, while scheme No. 11 was dropped from further consideration.

Schemes No. 12 and 13 are similar in the actuation-ring-link idea, but scheme No. 13 includes a series of slots to continuously position the shroud, while scheme No. 12 is more applicable to two position operation where the shroud is located radially by ring stops at both ends of travel. By allowing greater circumferential travel for a given radial change, scheme No. 13 is expected to provide better clearance control by reducing the sensitivity of clearance changes to uncertainties in control position. Scheme No. 13 is then representative of this type of scheme. Control considerations will determine which technique is superior.

Scheme No. 33. Mechanical Cam Actuated Shroud. Scheme No. 33 was selected as being representative of mechanical linkage schemes as applied to the high turbine. The severe operating environment and mechanical tolerance required due to thermal growth must be carefully evaluated to determine the practicality of mechanical cams in this environment.

By comparison to scheme No. 13, this scheme offers lower leakage, reduced size, and better clearance control. Specifically, the scheme has fewer linkages, hence less control loss due to tolerance buildup, and the shroud positioning slots are located such that no pressure sealing is required across them. The scheme has advantages in both the compressor and turbine and will be used in place of No. 13 in the compressor.

Scheme No. 9. Pneumatic/Thermal Variable Tip Shroud. Scheme No. 9 is retained as a candidate scheme.

Schemes No. 17 and 18. Bellows Actuated Shroud. Schemes No. 17 and 18 are both pneumatic bellows actuation schemes, the only difference being that scheme No. 17 controls the blade shroud gap only while scheme No. 18 controls both the blade shroud and vane gaps simultaneously.

Both schemes will be retained with the view that they are different applications of one clearance control device and will be represented by the more general scheme No. 18.

Scheme No. 19. Case Cooling — Air. Scheme No. 19 is a case cooling scheme using fan duct air flowing axially along a split case compressor. It is not applicable to built-up case construction because the protruding flanges significantly decrease the cooling effectiveness. The compressor case of this study will be built up; hence this scheme is not practical for this study. It will be dropped from further consideration in lieu of other fan air cooling schemes suitable to built-up cases.

Schemes No. 20 and 31. Fan Air Cooled Cases. Schemes No. 20 and 31 are fan duct air case cooling schemes for segmented cases. They consider the compressor and turbine respectively. Scheme No. 31 has improved cooling effectiveness, tube geometry, and split rails, and will be retained as the concept for both compressor and turbine. Insulation will be considered to improve the effectiveness.

Schemes No. 21, 21A and 32. Case (Rail) Heating and Cooling. Scheme No. 21 is a compressor air case heating and cooling scheme designed for a split case compressor. It is not applicable to this study for the same reasons given for scheme No. 19. An alternate scheme, No. 21A, uses heating and cooling of the cases but is adapted to segmented construction in place of scheme No. 21. Scheme No. 32 is conceptually the same but applied to the high turbine and will be retained for consideration as well.

Schemes No. 22 and 22A. Case Heating. Scheme No. 22 uses low pressure turbine air to heat the cases during pinch points, hence opening clearances. It is for split case shrouds and is not applicable to this study (see discussion of scheme No. 19).

Scheme No. 22A uses the scheme of heating cases with turbine exit air but adapts it to the segmented cases of this work. This modified scheme (No. 22A) will be considered in place of scheme No. 22.

Schemes No. 23 and 24. Disk Bore Heating and Cooling. Schemes No. 23 and 24 control the disk temperatures with compressor interstage air to provide the required ACC. These techniques have slow response, limited clearance control capability, and create severe and unacceptable disk life limitations. For these reasons the techniques were dropped from further consideration.

Scheme No. 25. Floating Vane and Case. Scheme No. 25 is a passive scheme which was dropped from further consideration as it was not within the scope of the program.

Scheme No. 26. Electrically Heated Shroud. Scheme No. 26 provides clearance control by electrically heating the shroud with imbedded resistance heaters. The scheme requires a separate electrical power supply because of the amount of power required and has major reliability and development problems. Previous experience with electrical systems which are integral with engine cases have shown poor reliability and durability, so it is expected that a major development effort would be required for this scheme. For these reasons, this system was dropped from further consideration.

Scheme No. 27. Electrically Heated Seal Land. Scheme No. 27 is an application of scheme No. 26 to the compressor exit seal. It is not practical for this application because the large temperature change required for a significant clearance change ($\Delta T = 250° R$ for 0.010-in. clearance change) and would require operating temperature levels beyond allowable levels of available materials. This in conjunction with the reasons given for dropping scheme No. 26 caused this scheme to be dropped from further consideration.

Schemes No. 28, 29, and 30. Compressor Exit Seal Applications. Schemes No. 28, 29, and 30 are applications of schemes No. 17, 8, and 6A, respectively, to the compressor exit seal. They were retained for consideration as being representative of ACC on internal air seals. Scheme No. 29 will be modified to configuration No. 29A, which leaves the actuation device undetermined (similar to scheme 8) until completion of the control study.

Schemes No. 34, 35 and 42. Externally Cooled Case Air Deflector. Schemes No. 34, 35 and 42 function by deflecting the duct air onto the cases to increase cooling and lower the case temperature. The expected range of control is small and the losses high because of the low efficiencies of such systems. Scheme No. 35 was retained as representative of this type of scheme because it provides the additional potential of reducing the cooling through the use of insulation, while having little additional penalty associated with it.

If the expected more efficient case cooling schemes (No. 31, 32) have surplus control capability and there appears to be a benefit for a less complex but limited actuation scheme, these schemes would be reconsidered.

Scheme No. 36. Blade Tip Erosion Compensator. Scheme No. 36 is a passive clearance control compensator and as such was outside the scope of the contract and was dropped from further consideration.

Schemes No. 38 and 38A. Thermal Fast Response Shroud Ring. Schemes No. 38 and 38A are similar to scheme No. 32 in that they control the HPT shroud location by controlling the shroud support ring or rail temperatures with high pressure compressor air. Schemes No. 38 and 38A are fundamentally different, however, in that they are fast response systems capable of tracking an engine transient, whereas scheme No. 32 is not. Scheme No. 38A was retained for further analysis because it is a fully ACC scheme whereas scheme No. 38 is not. Scheme No. 38 was dropped from further consideration.

Scheme No. 39. Thermal Fast Response Shroud Ring. Scheme No. 39 uses high pressure compressor air to cool and heat the low turbine cases. This idea will be retained for further analysis and be represented by scheme No. 38A.

Scheme No. 40. Compressor/Ingestion Cooled/Heated Cases. Scheme No. 40 poses severe control and design problems because of the fine control required of the bleed air to modulate ingestion. It is also similar to scheme No. 39 in many respects, and was dropped from further consideration pending positive results from scheme No. 39. Scheme No. 41 is less efficient than scheme No. 40 due to the additional waste of HPC air. For this reason and the reasons stated for scheme No. 40, it was also dropped from further consideration.

Schemes No. 28, 29A, 30. Rear Compressor Seals. These concepts were dropped because of inadequate payoff for controlling clearances in the rear compressor seal.

2.1.5 Final Schemes

The 12 schemes selected for more detailed evaluation are shown schematically in Figures 52, 53, and 54. A brief description of these schemes and some comments on their application are given below.

Mechanical Schemes. These types of schemes are generally categorized by a large number of precision moving parts. They offer a response rate capable of following clearance changes during normal engine transients and a large range of clearance variation. The clearance control is not expected to be precise due to tolerances, slip, and wear at the numerous joints and contact surfaces. The schemes are also expected to be expensive, heavy, bulky, and have maintainability and reliability penalties. In some cases they may not be applicable to high temperature environments.

Scheme No. 10A. Screw Actuated Stator and Shroud. The shrouds and stators are moved radially with a lever arm and sync ring driven screw. Six to eight segments with two or more supports per segment are required to get 90% effective clearance change due to circular distortion effects.

Scheme No. 33. Cam Actuated Shroud. The cam actuated shroud has angled slots in its side rails which are engaged by fingers attached to a sync ring. The shrouds are restrained to move radially only, so when the sync ring is rotated the fingers ride up or down the angled slots forcing the shroud radially out or in. This scheme provides for both gas path sealing and shroud cooling so is applicable to the HPT.

Scheme No. 6A. Axial Shroud Shift. The compressor shroud is a conical ring that translates forward and aft. Axially translating the conical ring with respect to the blades causes a radial clearance closedown whose magnitude is proportional to the flowpath slope. Actuation is stage-by-stage.

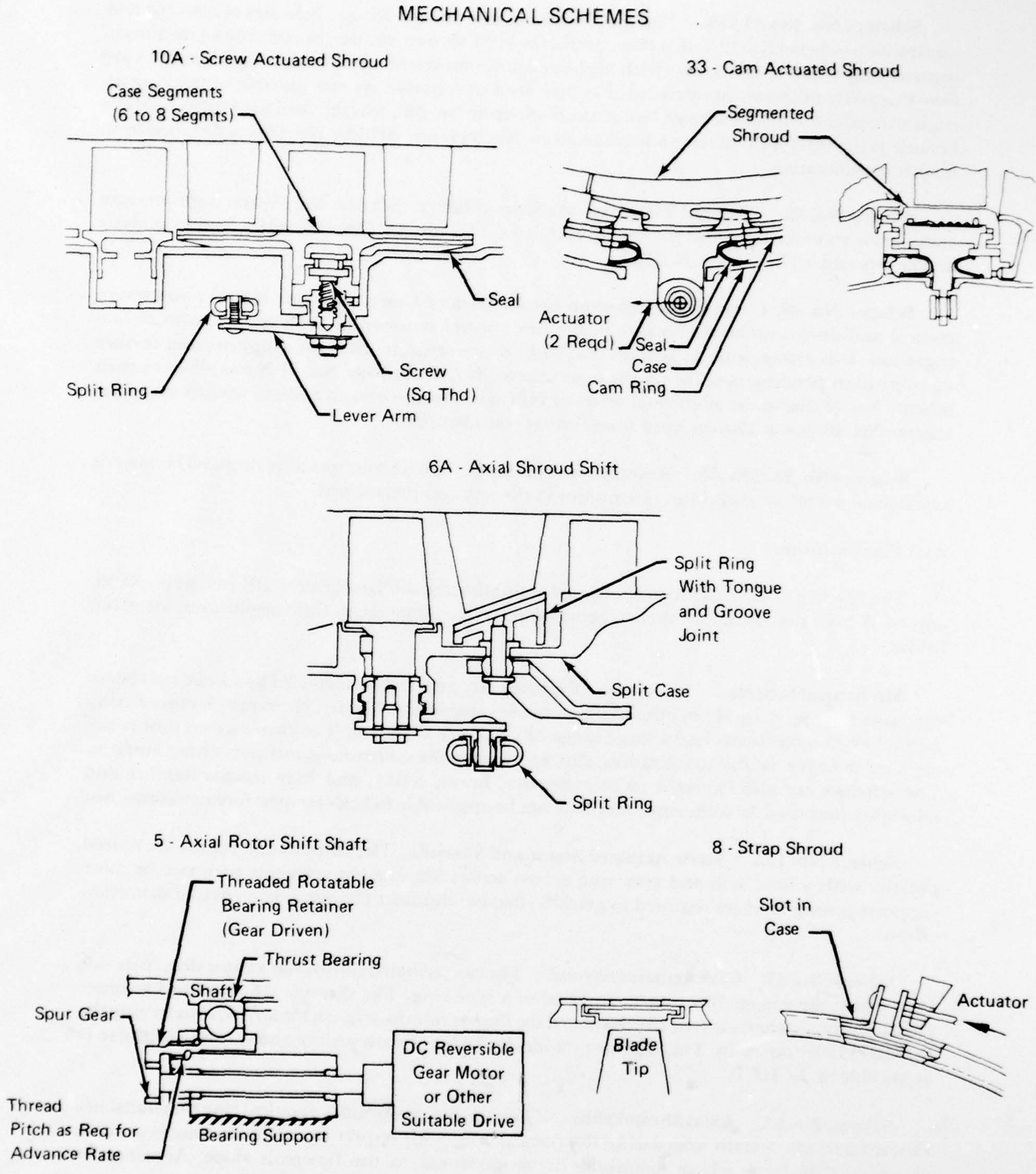


Figure 52. Mechanical Schemes

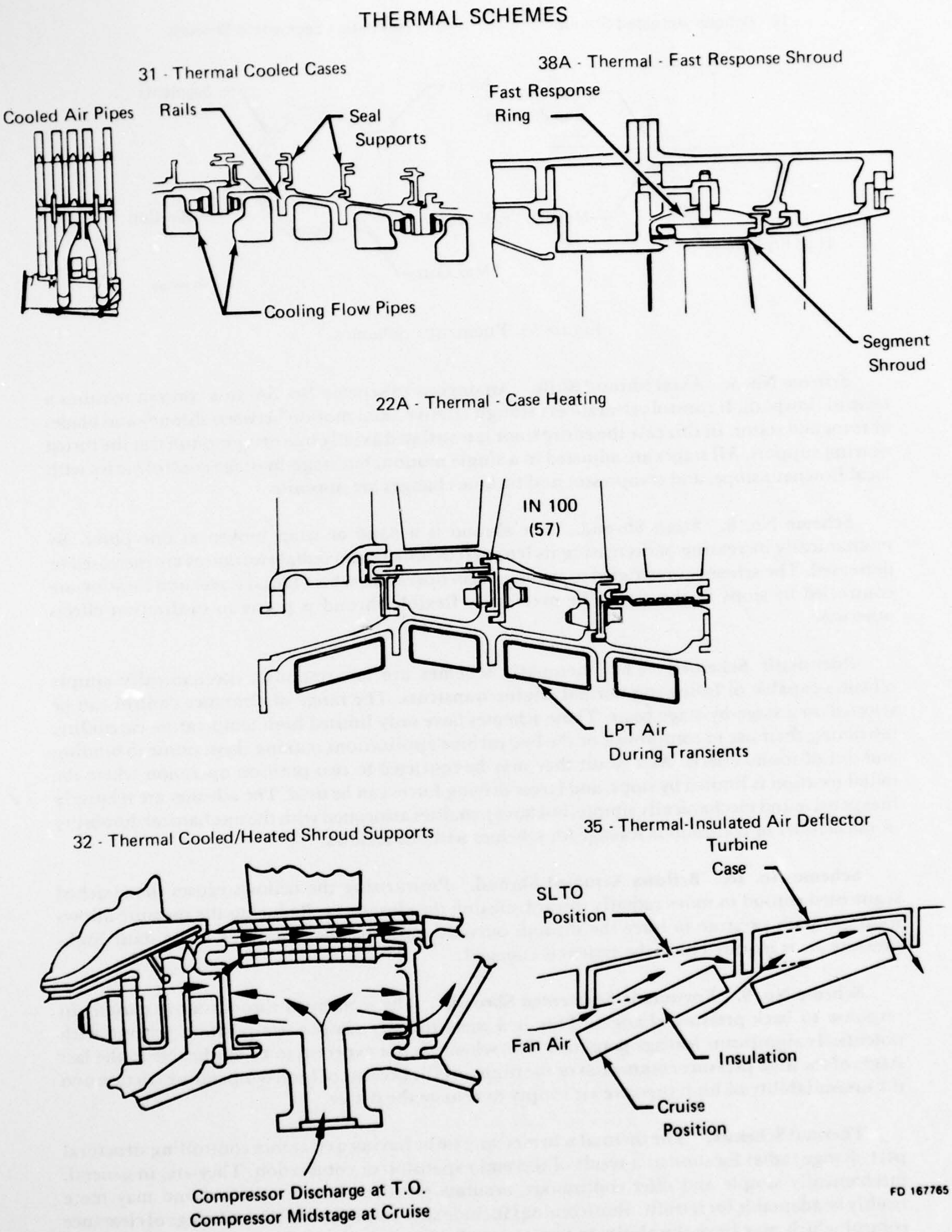


Figure 53. Thermal Schemes

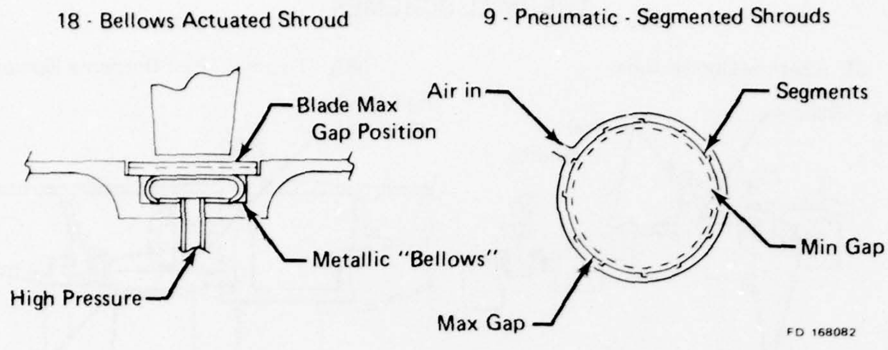


Figure 54. Pneumatic Schemes

Scheme No. 5. Axial Shroud Shift. Analogous to scheme No. 6A, this concept requires a conical flowpath. It controls clearances through relative axial motion between shrouds and blades or rotor and stator. In this case the entire rotor is translated axially by a drive mounted at the thrust bearing support. All stages are adjusted in a single motion, but stage-by-stage control varies with local flowpath slope, and compressor and turbine changes are opposite.

Scheme No. 8. Strap Shroud. The shroud is a band or strap broken at one point. By mechanically increasing or decreasing its length (circumference) radial clearances are increased or decreased. The scheme is restricted to two-position operation where radial travel and location are controlled by stops in the case. The necessarily flexible shroud is prone to ovalization effects otherwise.

Pneumatic Schemes. The pneumatic schemes are fast-response, mechanically simple schemes capable of following normal engine transients. The range of clearance control can be selected on a stage-by-stage basis. These schemes have only limited high temperature capability, restricting their use to compressor or the low turbine applications making them prone to binding and out-of-round effects. As a result they may be restricted to two-position operation where the radial location is limited by stops, and larger driving forces can be used. The schemes are relatively inexpensive and mechanically simple, but have penalties associated with the mechanical durability of the bellows or continuous leakage for schemes without bellows.

Scheme No. 18. Bellows Actuated Shroud. Pressurizing the bellows causes the attached segmented shroud to move radially inward, closing the clearances. Reducing the pressure allows local gas path pressure to force the shrouds outward, opening the clearances. Only static high-pressure air is required once the system is engaged.

Scheme No. 9. Pneumatic Segmented Shrouds. The segmented shrouds move radially in response to back-pressure changes. This is a mechanically simple two-position scheme with potentially significant leakage penalties. The scheme is not expected to be applicable to the last stages of the high pressure compressor or the high turbine because of high temperature friction and the unavailability of high pressure air supply to actuate the device.

Thermal Schemes. The thermal schemes operate by having a clearance controlling structural part change radial location as a result of thermal expansion or contraction. They are, in general, mechanically simple and offer continuous, accurate positive clearance control and may more readily be adaptable for retrofit. Shortcomings include slow response and limited range of clearance control which may limit the ability to track normal engine transients.

Scheme No. 20. Thermal Cooled Cases. Cases are cooled with fan duct or front stage compressor air. High cooling effectiveness is possible with impingement of cool air on compressor rear stages or turbine. Cooling air is turned off prior to pinch points and transients which allows cases to heat up and increase clearances. This scheme suffers a continuous performance penalty due to continuous bleed air requirements.

Scheme No. 21A. Thermal Heated Cooled Cases. Cases are heated at idle points and cooled at cruise points. This scheme is a combination of schemes No. 20 and 22A where additional range of clearance control is obtained at the cost of added system complexity.

Scheme No. 22A. Thermal Case Heating. Cases are heated at idle points with low turbine air to avoid pinches during subsequent transients to higher power. Schemes are off during cruise resulting in no bleed air performance penalties but may have limited range of response.

Scheme No. 35. Thermal Insulated Air Deflector. Insulation is mechanically mounted to swing away from the case during cruise diverting fan air onto case for cooling when tighter clearances are required. The insulation is pressed against the case during pinch points insulating the case from the cooler fan air when hotter structure, hence larger clearances, are required. The scheme is only applicable to the fighter engine where fan duct cooling is significant.

Scheme No. 38A. Thermal-Fast Response Shroud. This scheme combines the fast response of mechanical schemes with the simplicity and accuracy of thermal schemes. In this scheme, a transpiration or impingement cooled ring controls the shroud locations. The ring temperature is controlled by modulating air from two different compressor stages depending on the required flight point and desired clearance.

2.2 CONTROLS

2.2.1 Controls Overview

The actuators and linkages required to control the final 12 schemes were sized, and the cost, weight, reliability, and development risk for each was determined. These estimates are expected to have a high confidence level as they were based on hardware currently in use. A summary of the control requirements is given in Table 4 where the control response rate, level, range, type, and description are given for each ACC scheme.

The control "response rate" is a measure of the time to fully actuate the controls. It is set by either the typical engine response (3 to 5 sec for an acceleration transient) or the intrinsic scheme response rate, whichever is larger. The time scales are fast $\leq$ 1 sec, 1 $<$ med $\leq$ 5 sec, 5 sec $<$ slow. The control "level" is described in Section 2.2.2. The control "estimated range" is a measure of the radial clearance change possible with each scheme. The control "type" and "description" identify which of the eight controls ($A \rightarrow H$) described in Section 2.2.4 are applicable to each of the ACC schemes.

Table 5 summarizes the LCC inputs for each control system and for each component application. Referring to Table 5, ACC mechanical scheme No. 18 (Bellows Control Shroud) uses control scheme D which weighs 15 lb, costs $2,000, has a mean time between failure (MTBF) of 25,000 hr, and responds in less than 1 sec. One control is required for HPT stages 1 and 2, or HPC stages 10 through 13, or HPC stages 6 through 9, or LPT stages 1 and 2. However, two would be required for controlling stages 6 through 13 of the HPC as a unit.

TABLE 4. CONTROLS REQUIREMENTS FOR FINAL ACC SCHEMES

	Controls				
	Response Rate	*Level*	*Range*	*Type**	*Description*
5 — Axial Rotor Shift	2	1,2,3	1	A	Ball Screw
6A — Axial Shroud Shift	1	1,2,3	1	B	RCVV**
8 — Strap Shroud	1	1,2,3	1	B	RCVV
9 — Pneumatic/Thermal Tip Shroud	1	1	1	C	Pneu Closed Sys
10A — Screw Actuated Tip Shroud	1	1,2,3	1	B	RCVV
18 — Bellows Actuated Shroud	1	1,2,3	1,2	D	Pneu Closed Sys
31 — Thermal Cooled Cases	3	1	1	F	Pneu Flowing Sys — One
32 — Thermal-Heated/Cooled Cases — HPC Air	3	1	1,2	G	Pneu Flowing Sys — Mix
22A — Thermal-Case Heating	3	1	1	F	Pneu Flowing Sys — One
33 — Cam Actuated Shroud	1	1,2,3	1	B	RCVV
35 — Thermal — Insulated Air Deflector	3	1	1	E	RCVV
38A — Thermal — Fast Response Shroud	1	1,2,3	1	H	Pneu Flowing Sys — Mix

Response Rate	*Level*	*Est Range*	*Type*
1-Fast	1-On/Off	1->20 Mils	8 Schemes
2-Med	2-Open Loop	2-10-20 Mils	Identified
3-Slow	3-Feedback	3-<10 Mils	(A-H)

*See Section 2.2.4 for An Explanation of Those Categories

**Rear Compressor Variable Vane Angle Positioning Controller

TABLE 5. ACC — CONTROL SYSTEM SUMMARY

ACC Schemes	*Control Scheme*	*Weight (lb)*	*Acquisition Cost $*	*Reliability MTBF (hrs)*	*Response (sec)*	*Accuracy % of Point*	*Develop. Risk*
5	A	20.0	11,000	7,500	1	+1.5	Low
6A	B	10.0	6,000	11,000	1	+1.8	Low
8	B	10.0	6,000	11,000	1	0.8	Low
10A	B	10.0	6,000	11,000	1	0.8	Low
33	B	HPT-12#	HPT-6500	11,000	1	0.8	Low
		HPC-10#	HPC-6000	11,000	1	0.8	Low
9	C	3.0	1,000	6,500	<1	—	Low
18	D	15.0	2,000	25,000	<1	+0.1	Low
35	E	4.3	1,600	17,000	<1	—	Low
22A,31	F	4.0/7.0	800/800	13.5k/6.5k	<1/<1	—	Low
32	G	12.0	3,000	6,500	<1	—	Low
38A	H	15.0	5,000	5,000	Fast(?)	+0.2	Moderate to High

ACC Schemes	*HPT 1&2*	*HPC Stg 10-13*	*HPC Stg 6-9*	*HPC Stg 6-13*	*LPT*
5	1	N/A	N/A	1	N/A
6A	1	—	1	1*	1
8	N/A	1	1	1*	1
10A	N/A	1	1	1*	1
33	1	1	1	1	1
9	N/A	1	1	1	1
18	N/A	1	1	2	N/A
35	1	1	1	1	1
22A	1	1	1	1	N/A
32	1	1	1	1	1
38A	1	N/A	N/A	N/A	N/A

The ground rules for the control estimates were:

1. Controls were required to respond faster than the normal clearance change during maneuvers or throttle transients (response time $<$ 1 sec). For mechanical and pneumatic systems this resulted in clearance changes occurring on the order of 1 sec, while for thermal schemes the clearance response rate was controlled by transient thermal response of the structures.

2. The estimates are for controls only. Brackets, plumbing, gears, levers and other linkage items are not included in the controls portion of these estimates, but are included in the total system cost. The control requirements for the fighter and transport are the same, with the exception that the fighter has two LPT stages while the transport has five LPT stages. This may require the transport to have a larger size actuator.

All actuators except air valves will be located external to the fan duct.

General Control Considerations. Operating with feedback control to maintain the clearance desired will require the sensor to be mounted on and move with the active member. This installation problem may eliminate closed loop control from some schemes.

Utilizing high pressure fuel as the actuating fluid must be carefully reviewed for each application relative to engine safety. On advanced engines fuel is kept outside the fan ducts for this reason. It may result in a problem in positioning the RCVV's due to the additional linkages required.

The real time control computation required for all schemes was accomplished by an electronic engine control. It is assumed that the sensed parameters necessary for this activity can in fact be obtained. For each specific concept the required parameters must be identified and the precision of the sensors established. This in-depth activity will not be accomplished as part of the current program. When the work is accomplished, the results may impact the overall effectiveness of a specific ACC concept.

Failure modes of the control system are a generic problem that is common to all of the schemes. Since there will always be a failure mode in the control that could lead to a failure of engine parts, consideration has been given to redundant systems to provide fail-safe operation. While this may not always be possible when weight and complexity negate any gain achieved with the clearance control concept, in all cases a fail open, or tolerant failure mode for the clearance control system is required. A detailed failure mode analysis would be required in order to define the failure modes for ACC schemes and controls before final incorporation in an engine could be recommended.

2.2.2 Control Types

The three types of control schemes considered are the on/off, open loop, and feedback controls. The on/off scheme provides simple two-position actuation optimized at one flight point. Since the clearance does not vary significantly over the cruise or dash legs (see Table 6) a simple system of this type can accurately achieve nearly all the benefit available over an entire mission with a single closedown. The control can be activated for the appropriate condition using presently monitored engine operating parameters. For pneumatic and mechanical systems using on/off controls, the shroud is restricted to two-position operation where the limit of travel (and therefore positional accuracy) is set at the outer airseal by stop grooves machined into the cases. The on/off operation can be fast or slow, but the clearance limit cannot be adjusted without disassembling and replacing the outer air seal (OAS). Thermal on/off schemes are adaptable to different limits of clearance closedown by simply altering cooling airflow level. This can be done easily with external changes. The controls are relatively inexpensive, and the positional accuracy is good for this off-the-shelf scheme.

TABLE 6. SUMMARY OF CLEARANCE CLOSEDOWNS

Scheme No.	Description		Fighter 1.2/10K	Fighter 0.9/35K	Fighter Effective	Transport Cruise
5	Axial Rotor Shift	A[a]	0.030	0.029	0.029	0.011
		B	0.027	0.029	0.027	0.002
		C	0.021	0.025	0.021	0.003
6A	Axial Shroud Shift	B	0.027	0.029	0.027	0.002
		C	0.021	0.024	0.021	0.003
8	Strap Shroud	B	0.027	0.029	0.027	0.002
		C	0.021	0.024	0.021	0.003
		D[a]			0.035	0.025
9	Pneumatic Segmented Shroud	B	0.027	0.029	0.027	0.002
		C	0.021	0.024	0.021	0.003
10A	Screw Thread Actuated Shroud	B	0.027	0.029	0.027	0.002
		C	0.021	0.024	0.021	0.003
18	Bellows Actuated Shroud	B	0.027	0.029	0.028	0.002
		C	0.021	0.024	0.023	0.003
31	Thermal — Case Cooling	A	0.021	0.009	0.015	0.011
		B	0.006	0.003	0.005	0.002
		D				0.020
32	Heated and Cooled Supports	A	0.030	0.025	0.025	0.011
		D			0.035	0.025
22A	Air Tube Case Heating	A	0.014	0.006	0.010	0.011
		B	0.008	0.007	0.007	0.002
33	Cam Actuated Shroud	A	0.030	0.029	0.029	0.011
		B	0.027	0.029	0.027	0.002
		C	0.021	0.029	0.021	0.003
35	Insulated Air Deflector	A	0.017	0.005	0.011	0.011
38A	Thermal — Fast Response Shroud	A	0.030	0.019	0.025	0.011

[a]Letters Designate Stage Groupings As Follows:

A = HPT 1 and 2
B = HPC 10-13
C = HPC 6-9
D = LPT - All

Open loop controls utilize more comprehensive engine operating information and a mathematical model of the engine clearance as a function of operating conditions in order to set the clearances at more than one operating point. This type of system requires that the clearances be set and held at some intermediate position depending on the operating point and that the linkage or actuation scheme has a high positional accuracy between stops.

Feedback control assumes that the clearance between the blade tip and the outer airseal is continuously measured during the mission. For the purposes of the study such a clearance sensor was assumed to exist and to have sufficient accuracy, although no estimate could be made of its LCC. Feedback control also required that the ACC scheme be capable of high positional accuracy with little hysteresis.

2.2.3 Control Type Evaluation

Inaccuracies in positioning multi-position or variable mechanical ACC devices in engines are typically ±10 mils at best due to tolerances in the linkage and device. The large temperature excursions, significant loads, and severe environment prohibit micrometer accuracy in working engine parts. To avoid repeated rubs the best average closedown achievable would then be 10 mils less than the maximum available. Based on the clearances available for closedown at cruise (Table 6), the positioning inaccuracy is fully 33 to 100% of these available clearances. Even at the lowest figure of 33% (i.e., available clearance = 0.030 in.), one-third of the available benefit cannot be achieved because of positional inaccuracies. In addition, a review of the mission profiles shows that only 11% of the transport and 31% of the fighter missions can benefit from more than simple on/off controls. On the benefits side alone, it costs more to have active feedback on mechanical systems than can be gained. Considering the additional weight, cost, maintenance, and development required for such schemes, anything other than on/off controls are undesirable for mechanical schemes.

Pneumatic segmented shrouds are only applicable to on/off controls for the reasons given in the scheme description section. Open loop and feedback controls are conceivably applicable to pneumatic bellows but the regions of the mission which can benefit from it are small, and the development costs and operating penalties associated with the system must be accounted for. Case controlling ACC thermal schemes cannot utilize open loop or feedback control to track clearances because of their slow response. Thermal schemes can potentially utilize advanced controls to set different steady state clearance levels at different flight points. The special fast response thermal schemes can utilize more advanced controls and have intrinsically more accurate positioning than the mechanical or pneumatic schemes. These schemes may be cost effective in the higher control modes provided the required range of clearance control is always available, and ovalization due to circumferential thermal distortions can be overcome. The more sophisticated controls have additional problems beyond accuracy of control. The open loop system assumes that an accurate clearance prediction computer algorithm based on measured engine parameter inputs (N_2, CET, etc.) can be formulated. A feedback control requires development of an accurate, durable, flightweight, field operational device to monitor clearances.

Open loop and feedback controls are capable of tracking changing clearances during transient and steady state mission legs, while the on/off controls are restricted to the steady state legs only. As a result these higher level controls allow ACC benefits over larger portions of the mission then do the on/off controls. An indication of the benefit for higher level controls over simple on/off controls is the additional time during the mission when ACC can be used if higher level controls are employed. Table 18 gives a breakdown of the fighter and transport missions showing the portions of those missions that benefit from each level of control. For example, on/off controls can be activated for 88 min of the 155 min mission, which corresponds to 57% of the mission time. By comparison the open loop controls can be activated for 117.5 min of the 155 min mission, or a total of 76% of the mission time. The added complexity, cost, weight, reliability, and positioning uncertainty of the higher level control must then be balanced against the performance and efficiency gains during the additional 19% (76-57%) of the mission when open loop controls are activated and on/off controls are not. For some missions and cycles open loop controls may allow for tighter clearances over the same mission legs.

The length of time during which ACC is activated is only one measure of the potential payoff for higher level controls. A possibly more representative measure is the amount of fuel burned during that portion of the mission when the controls are activated. This is a useful measure particularly for the transport where the A/C size and LCC are more closely tied to the amount of fuel required. An estimate of the actual amount of fuel saved, or the reduction in A/C size or LCC with higher levels of control is not possible without rederiving the mission and LCC trade factors for the improved performance with higher level controls. This task is beyond the scope of this work.

An estimate of the benefits can be made, however, by considering what portion of the fuel is burned on which legs. The higher level controls allow ACC to be active on more mission legs, hence during more fuel burning. The greater the percentage of the total fuel burned with a particular level control active, the greater the payoff for that level of control.

Table 18 lists the portion of fuel burned during which ACC is on, for the different levels of control. For example, on/off controls on the fighter are activated during 69% of the fuel burning, while open loop controls can be activated during 76% of the fuel burning. The added cost, complexity weight, reliability, and positioning uncertainty of the higher level of control must be balanced against the performance and efficiency gains during the additional 7% (76-69%) portion of the fuel burned when the higher level of control is active.

Feedback control concepts do not appear to be justified for this study because the portions of the missions where the additional benefits can be achieved are small, and the loss in positional accuracy may be a significant part of the total closedown available. This conclusion is mission and cycle dependent and needs to be reevaluated for each application, particularly in the selection of on/off vs open loop controls.

2.2.4 Control System Schemes

Descriptions of the control system schemes developed to control each of the final 12 ACC schemes follow. Schematics of these control systems are given in Figures 55 to 63.

Control A. This scheme provides the control system required for the ACC scheme No. 5 in which the whole high spool is shifted by moving the main shaft thrust bearing support axially. A schematic of the control system is given in Figure 55. Due to the high torque requirements, an air motor was selected to provide the driving force.

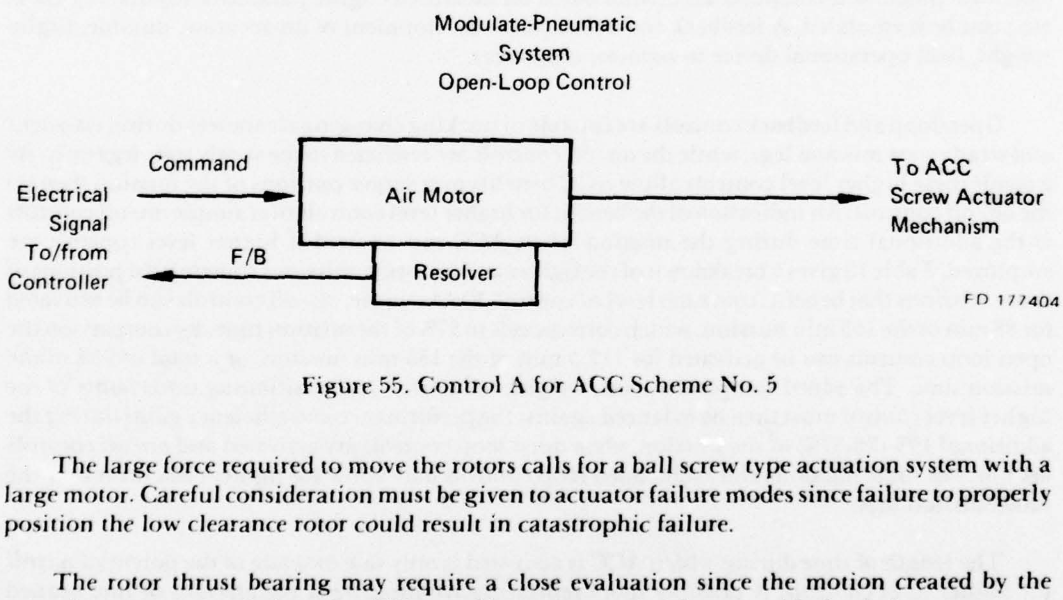


Figure 55. Control A for ACC Scheme No. 5

The large force required to move the rotors calls for a ball screw type actuation system with a large motor. Careful consideration must be given to actuator failure modes since failure to properly position the low clearance rotor could result in catastrophic failure.

The rotor thrust bearing may require a close evaluation since the motion created by the actuation system may induce durability problems not previously seen with the design.

The configuration lends itself to closed loop control with actuator position feedback for accurate positioning of the rotor shift mechanism.

Control B. This scheme (Figure 56) will satisfy the requirements of ACC concepts No. 6A, 8, 10A, and 33. Mechanical linkages are used to shift the compressor and turbine shrouds. A schematic of this control is shown in Figure 56. Dual feedback is incorporated for increased system tolerance to failures. The control system functions by positioning an external unison ring which is mechanically connected to the shrouds. The design of the lever and screw downstream of the sync ring will determine the effectiveness and accuracy of the concept.

Closed loop control can be easily incorporated by measuring actuator position. Positioning uncertainties due to tolerance buildup in the drive system must be accounted for by incorporating a dead zone into the feedback loop.

Control C for Scheme 9. This control, as shown in Figure 57, utilizes an on/off solenoid operated pilot valve to supply high pressure 13th-stage air. This air back-pressures the movable shrouds forcing them to a smaller diameter. When the actuation pressure is vented the internal pressure returns the shrouds to the maximum diameter thus increasing the blade clearances.

The control system is limited to on/off operation because of feedback problems arising from the use of compressor exit air.

Control D. ACC scheme 18 relies on the use of a thinwall, oval tube (bellows) to support and position a set of shroud segments. The pressure required to inflate the metallic bellows exceeds compressor exit pressure (by up to 400 psia). An alternate source of high pressure air is required.

The controls were powered by an airframe mounted high pressure nitrogen bottle (3000 psi) similar in size to a scuba diver's air tank (see Figure 58). Bottled air can be used since the system is closed, and the only air expended is in venting the system. The size of this tank should provide for up to 50 system cycles (activated only during steady state cruise conditions) and still provide 50% pressure reserve capacity in the tank. Pressure regulation is accomplished by an electrically controlled pressure regulating valve.

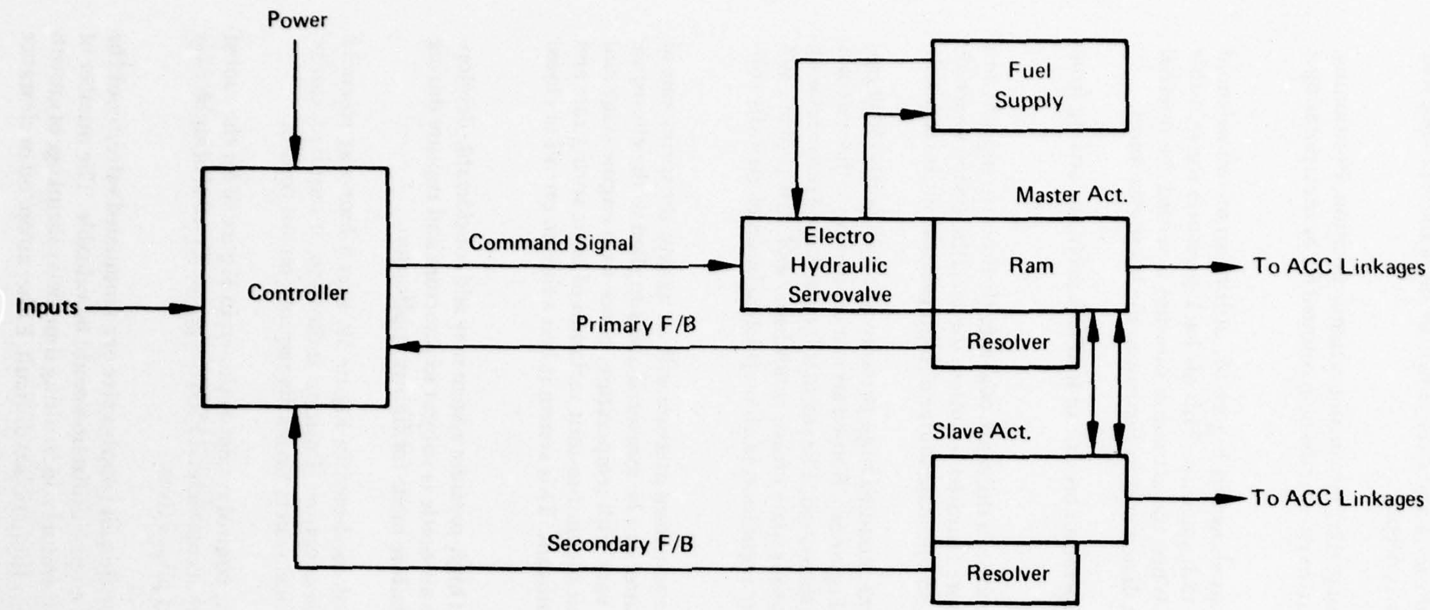
Precision of control will be difficult. The actuation pressure will act against the spring rate of the bellows and internal air pressure. The latter can be measured and supplied to the electronic control. The spring rate of the bellows will vary with temperature, hence with engine stage and flight point. A temperature can be sensed but the unit-to-unit variation of basic spring rate and change of rate with temperature may be significant. This system is best suited to on/off or closed loop feedback controls.

The requirement for an engine mounted high-pressure system may add considerable development risk to this scheme. The high pressure air bottle is subject to puncture and rupture during combat and this may have an unacceptable failure mode for fighter application.

Control E for Scheme 35. This control, as shown in Figure 59, uses a four-way solenoid operated valve to position a set of hydraulic actuators. Position indication, if required, can be provided to the airframe although a mechanical system primarily requires on/off control.

Control F for Schemes 22A and 31. The control system as shown in Figure 60 for the cooled case scheme is similar to the one used on current commercial P&WA engines. Control of air bleed is accomplished by means of solenoid operated pilot valves.

Open loop control, with either a two-position air supply valve or a modulated valve, would be difficult but depending on the mission and engine utilization could be valuable. The number of combinations of cooling airflow rate and temperature and resulting time-delay shrinkage of growth of cases would make accurate location at many flight points difficult. Either an on/off or clearance feedback signal would be prepared for this scheme.



	Master Act.	Slave Act. W/F/B	Slave Act. W/O F/B
Weight	5.8 lb	2.7 lb	2.0 lb
Cost	$4400	$1000	$520
Reliability (MTBF)	11,000 hr	17,000 hr	28,000 hr

Response = 100% Stroke Per sec
Accuracy = ±0.8% of Full Stroke (Does Not Include Mechanical Linkages)
Risk = Low

Notes:
1. Max Force = 470 lb/Act
2. Piston Dia = 2.0 in.
3. Stroke = 1.5 in.
4. Additional Elec Cable Weight = 1.5 lb/Engine

FD 167780

Figure 56. Control B for ACC Schemes No. 6A, 8, 10A, 33

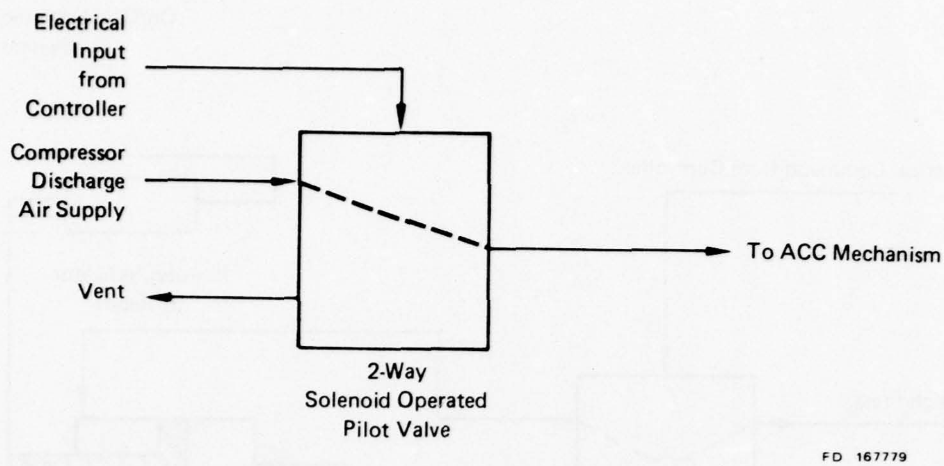


Figure 57. Control C for ACC Scheme No. 9

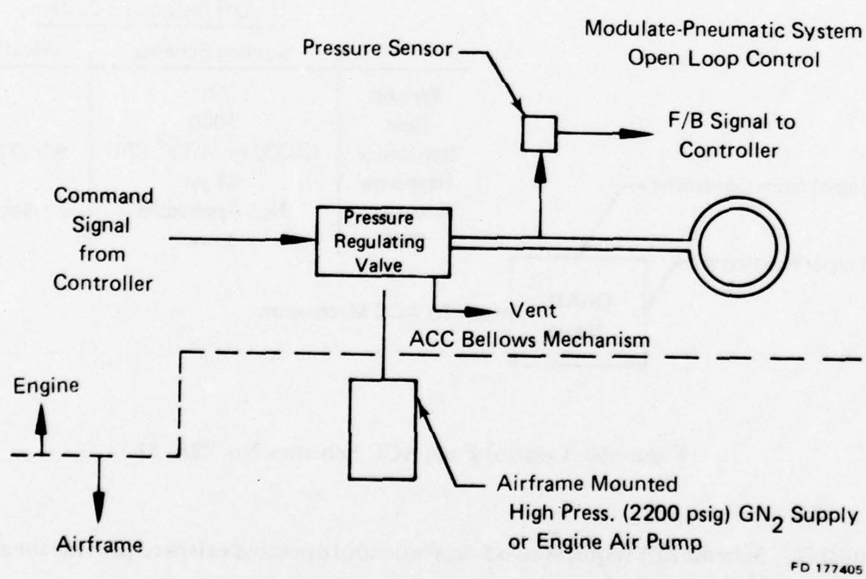


Figure 58. Control D for ACC Scheme No. 18

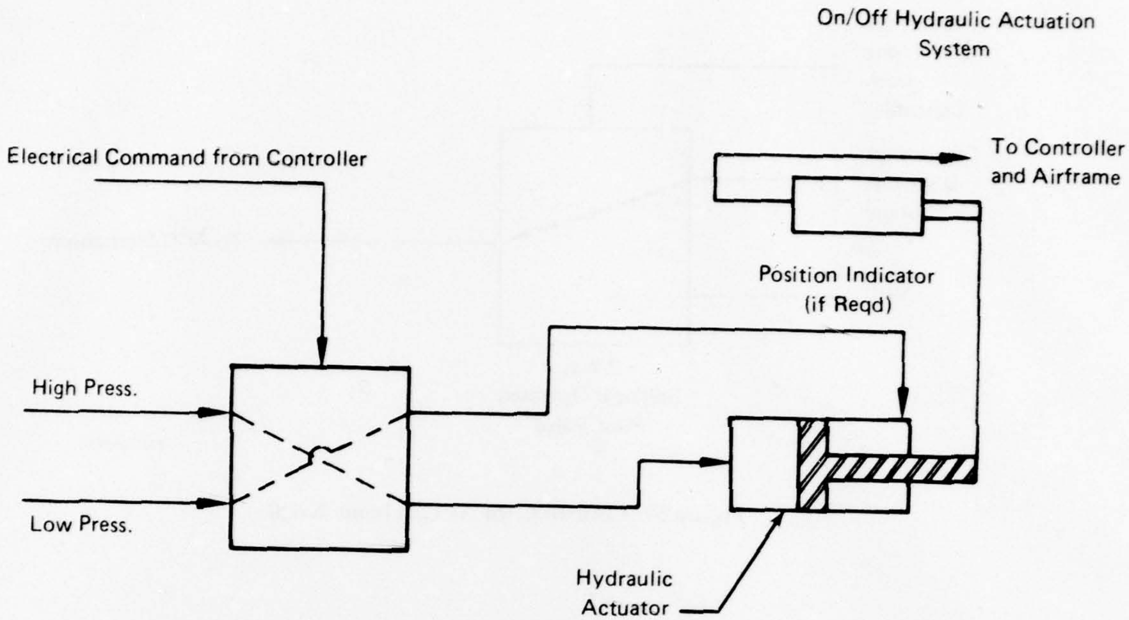


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Figure 59. Control E for ACC Schemes No. 22A, 31

On/Off Pneumatic System

	Cooling Scheme	Heating Scheme
Weight	7 lb	4 lb
Cost	\$800	\$800
Reliability	13,000 hr at 10^3 EFH	6,500 hr at 10^3 EFH
Response	<1 sec	<1 sec
Accuracy	Not Applicable	Not Applicable
Risk	Low	Low

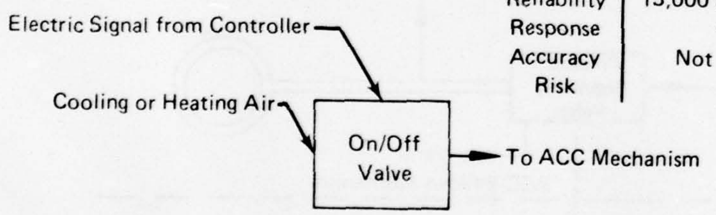

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Figure 60. Control F for ACC Schemes No. 22A, 31

Control G. Scheme 21A requires two 3-way solenoid operated valves to provide the airflow as shown in Figure 61.

The system operates as a modified on/off control with two different on positions. During the heating mode, 13th-stage air is bled by the heating valve, circulated through a manifold, and exhausted through the cooling valve. During the cooling mode, 7th-stage air follows the reverse path. Each valve also provides positive airflow shutoff for mission points where ACC is required to be off.

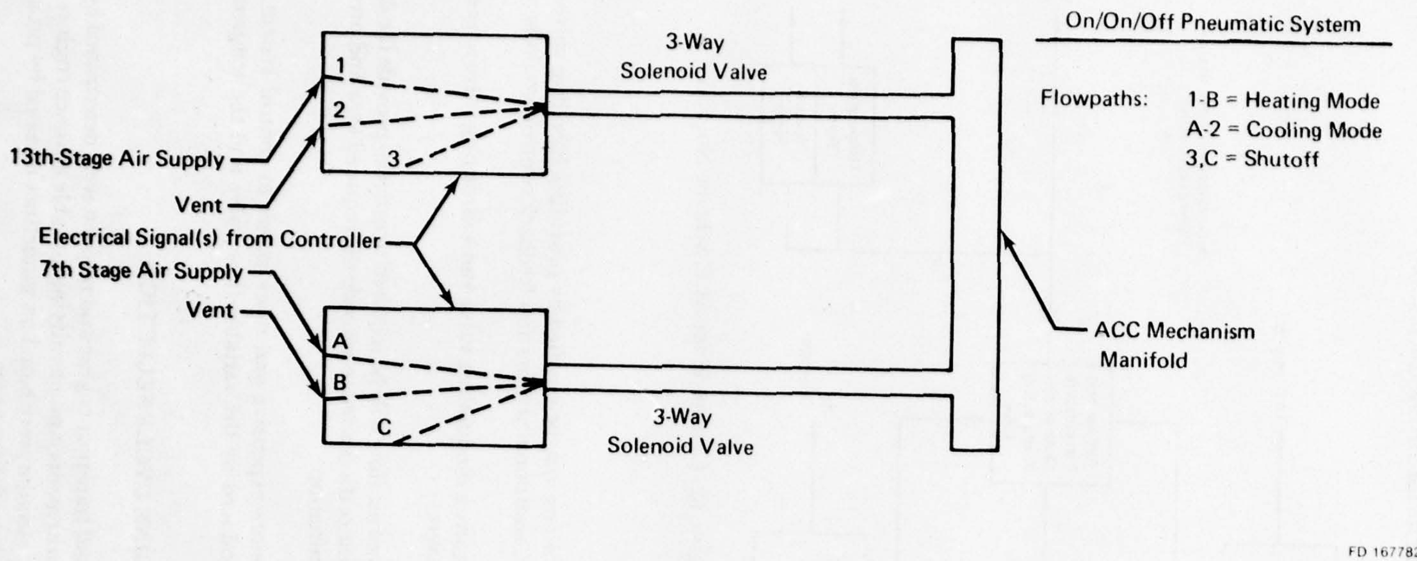

Figure 61. Control G for ACC Scheme No. 21A

Control H for Scheme 38A. This control, as shown in Figure 62, is a variation of control G. A flow and temperature control valve provides a mixture of 7th- and 13th-stage air to the ACC manifold to set the clearance as required. Open-loop modulated control is provided by sensors that monitor pressure and temperature for airflow calculations.

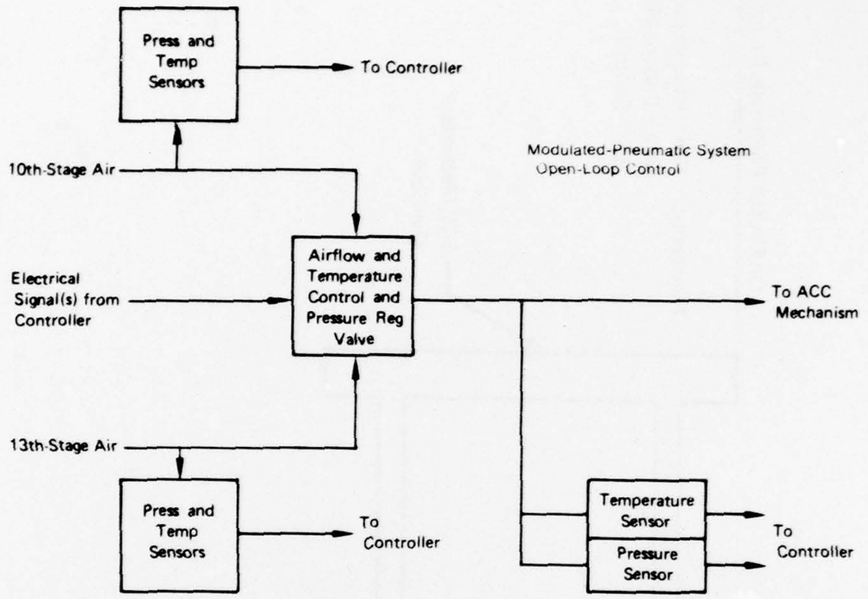

Figure 62. Control H for ACC Scheme No. 38A

Additional flight conditions may be satisfied by providing blending valves (and thus a more complex control). However, additional sensors and feedback control would be required.

This scheme would require a modulating valve and a throttling valve to provide variable flow from the two compressor stages.

Accurate measurement of air flow will be required in order to provide the desired control; this may involve the use of in-line orifices sized to provide the required flow and pressure and temperature sensors for flow determination.

This system will be more expensive and more prone to control system failure due to the increased complexity introduced by the variable flow valve and the temperature and pressure sensors required.

2.3 MISSION AND ENGINE CYCLE SELECTION

The baseline fighter and transport engine and mission were determined by reviewing current and advanced mission requirements, and identifying suitable advance engines for those missions. Both mission and engine selection were based on guidelines dictated by program objectives and practical limitations. These guidelines were:

Mission Selection

1. Missions for both low bypass ratio (fighter) and high bypass ratio (transport) engines would be studied.

2. Missions would be indicative of projected future requirements.

3. Current fleet makeup and usage would be weighed.

4. Mission analysis would be available.

5. Projected demand would be considered.

Engine Selection

1. Engines for both fighter (LBPR) and military transport (HBPR) would be considered.

2. Engine geometry and performance would be indicative of advanced requirements.

3. Existing thermal and structural models could be adapted for use in clearance determination.

Mission and engine selection would be based on the above criteria subject to the program objective that an evaluation of the net benefits of ACC across the range of military aircraft applications is desired.

2.3.1 Mission Selection

Consistent with these guidelines and program objectives, the missions selected were the Advanced Tactical Fighter (ATF) and the C-141 replacement strategic aircraft. These aircraft provide the best mix of advanced near term applications and performance with significant projected usage, while being generally representative of fighter and transport applications, respectively.

Fighter Mission Selection. The fighter missions reviewed for this study were the F-4, F-14, F-15, F-16, F-18, F-111 ATF and VSTOL-B. A summary of aircraft statistics is shown in Table 7, where yearly fuel usage, size, mission and number of aircraft indicate the relative mission requirements and fuel consumption of the various aircraft. As is apparent from this table, fighter aircraft usage in terms of fuel consumed is expected to be balanced with no one aircraft dominating. Potentially significant LCC benefits for ACC are not primarily identified with any one aircraft alone nor with any one particular mission.

The F-14, F-15 and F-18 aircrafts are fixed production designs which would be limited to retrofitting of the ACC schemes. Selection of one of these aircraft as the baseline unfairly penalizes ACC in an evaluation by not allowing full advantage of the performance improvements to be taken.

Use of the next generation of aircraft as the baseline allowed fully integrating the ACC into the design. This resulted in the aircraft engine being resized and rematched in response to improvements. The next generation fighter aircraft considered were the ATF and VSTOL-B. These aircraft are envisioned to have a multi-mission role and may be required to perform deep strike and/or battlefield interdiction.

TABLE 7. LOW BPR CANDIDATES (FIGHTER)

BPR < 1							
Aircraft	*Mission*	*Engine*	*Weight K lb*	*BPR*	*W/S*	*Inventory*	*Yearly† Fuel Usage-Mgal*
F-14*	Multi-Role Fighter	TF30-P-412	59	0.9	106	520	250
F-15*	Air Superiority Fighter	F100	41.5	0.6	65	729	200
F-16*	Multi-Role Fighter	F100	25	0.6	75	1388	260
ATF**	Strike-Interdiction Fighter-Bomber	—	50	0.5-0.8	90	(1000)	190
VSTOL-B**	Vertical Take-Off	—	—	0.5-0.8	100	—	

*In Current Production
**Future Application
†REF: USAF Cost and Planning Factors

The ATF, a fixed wing single engine aircraft in the 40,000 to 50,000 TOGW class, is envisioned to have either a deep strike or battlefield interdiction mission. These missions are shown in Figure 63. The deep strike mission consists of a cruise leg, then a higher altitude supersonic dash to combat, and return. The battlefield interdiction mission also has a cruise leg, but performs a low-altitude supersonic dash to combat, and return. Aircraft designed for the latter missions are somewhat larger in order to perform the low altitude dash, but are capable of performing the deep strike mission as well. The battlefield interdiction mission is then the more general and will be considered representative of ATF usage. By comparison, the VSTOL-B does not appear to have sufficient development or definition at this time to be considered as a realistic near term application of ACC.

The ATF would provide the earliest potential opportunity to apply original equipment ACC to a representative fighter aircraft. The projected usage and number of such aircraft is sufficient for ACC benefits to significantly impact overall fighter fleet operations if clearance control proved beneficial. Based on the above considerations, the detailed mission profile used in the study is shown in Figure 64.

Transport Mission Selection. The Military Transports reviewed as possible transport mission for this study included the E4A(747) airborne command post, the C-141X strategic transport, the YC-14 15 tactical transport, the B-52, and the KC-135 tanker. The C-141X is a wide body C-141 similar to the C15B, but with a larger fuselage. The cargo box size is increased for outsize payloads. The first three applications would be new aircraft while the last two would be reengined existing aircraft.

Table 8 lists these aircraft along with design and usage information. As is apparent from this figure, the C141X and B52 combined are expected to account for nearly 70% of the fuel usage, a result of their being large inventory, four-engine aircraft with long missions.

Additional factors considered were that the C-141X Program is thought to be a more likely candidate for production than the modified B-52 at this time, and that benefits due to efficient improvement in a reengineering application (B52) are significantly different than in a new aircraft design (C141X) where the aircraft structure can be resized in response to engine performance improvements. Application to a new aircraft-engine provides a more realistic evaluation of the benefits of ACC than does artificially requiring the ACC to operate on a vehicle designed for some other level of engine performance or efficiency.

Based on the high fuel usage, new aircraft application, and expected mission application, the C141X mission was selected as the high bypass ratio application of this study. The detailed engine utilization and mission profile used in this study are shown in Figure 65.

A summary of ATF and C141X base aircraft information and ground rules is given in Table 9.

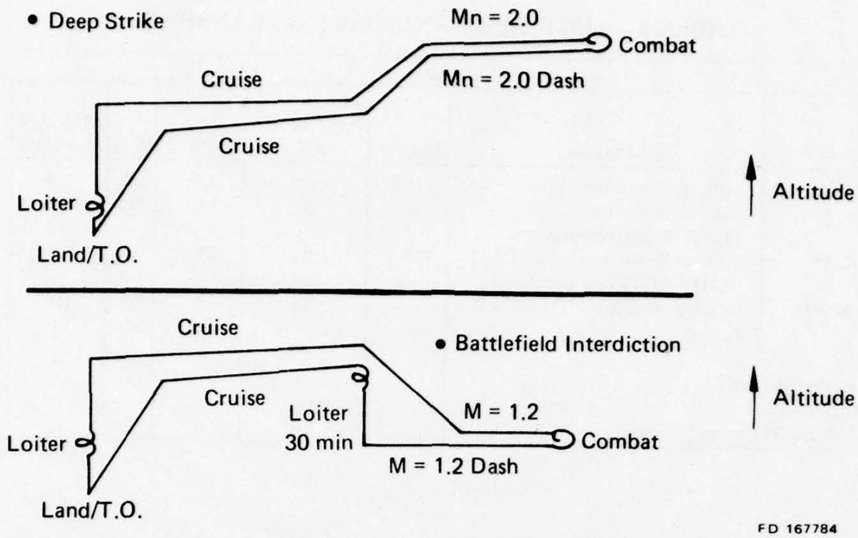

Figure 63. ATF Mission Profiles

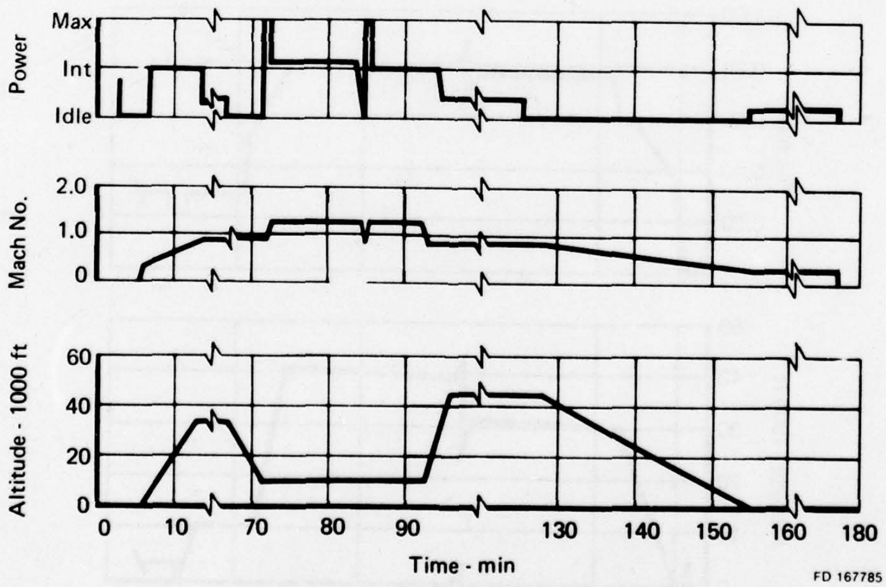

Figure 64. ATF Utilization for ACC Study

TABLE 8. HIGH BPR CANDIDATES (TRANSPORT)

BPR < 5							
Aircraft	*Mission*	*Engine*	*No. Engine/A/C*	*BPR*	*W/S*	*Projected Inventory*	*Yearly† Fuel Usage-Mgal*
E-4A (747)*	Airborne Command Post	JT9D	4	5.1	129	3	—
C-141X**	Strategic Transport (C-141 Replacement)	—	4	5+	126	277	650
YC-14/YC-15**	Tactical Transport (C-130 Replacement)	—	2	5+	125	277	190
Re-Engine B-52**	Strategic Bomber	—	4	5+	122	350	650
KC-135	Tanker	—		5+	124	487	375

*In Current Production
**Future Application
†USAF: Cost and Planning Factors

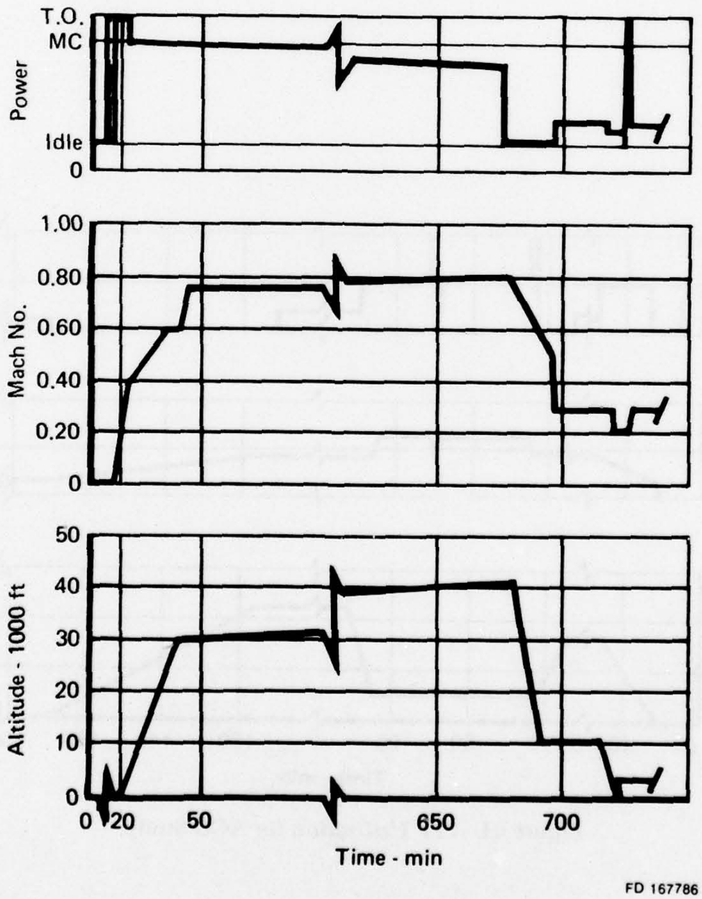

Figure 65. Transport Engine Utilization for ACC Engine Study

TABLE 9. BASE AIRCRAFT INFORMATION

	ATF	*C-141X*
TOGW, lb	50,000	381,000
OWE, lb	26,390	150,000
Payload	5,000	68,000
Total Fuel*	19,000	163,000
W/S	90	126
No. Engines	1	4
BPR	0.56	5.1
Max SL Thrust/Eng	27,700	24,300

*No External Fuel Used
OWE — Weight Empty
W/S — Wing loading

Ground Rules:

ATF	*C-141X*
Fixed Mission — Rubber Aircraft Rubber Engine	Fixed Mission — Rubber Aircraft Rubber Engine
5000 lb Payload Dropped Prior to Combat	68,000 lb Payload
P_s = Og at 3gTurn at 30k/0.9Mn	Field Length = 8000 ft

2.3.2 Engine Selection

Summary. The base engines selected for the fighter and military transport applications were an advanced F100 derivative, and an advanced transport engine with an F100 derivative core. These engines meet their respective program requirements, selection criteria, and have the added advantage of having the same core. This allows the basic structural analysis and incorporation of the individual schemes into the core to be common to both applications. The different base engines and missions did, however, generate different required clearances for the two applications.

The advanced F100 selected for the study used the inventory F100 geometry with the exception of a modified compressor case. The engine is a twin-spool augmented turbofan with a 3-stage fan, 10-stage HPC, 2-stage HPT, and a 2-stage LPT. The compressor case was modified to closely tie the blade outer airseals to the local position controlling case structure. This allowed more ready adaption of the large variety of ACC schemes uncovered.

Advanced transport engines built around the F100 family core engine provide the required advanced performance, analytical models, and system trades required for the study. The performance levels in TSFC, thrust to weight, and bypass ratio of these transport engines are comparable to the projected advanced transport engine levels of the near future. Using an F100 derivative engine has the additional advantage that ACC schemes drawn, weighted, priced, and otherwise evaluated in one core engine are directly applicable to the other engine. Differences in gas path conditions due to different performance points (M_N, ALT, PLA), low pressure compressor configuration, and HPC and HPT interstage performance are accounted for.

The transport engine selected is a 1-stage fan, 5-stage LPC, 10-stage HPC, 2-stage HPT, and 5-stage LPT design with a BPR of 5.1. The modified HPC case is again used to facilitate incorporation of ACC.

2.4 SCHEME DRAWINGS

Detailed sketches of the 12 final concepts were drawn into the base engines to provide working sketches from which LCC inputs (reliability, maintainability, weight, and cost) and system effectiveness could be determined. The actuation loads required to overcome static loads and generate the required transient response were calculated. All linkage and load transmission members were then sized based on these loads and allowable materials. The materials requirements were determined from estimated maximum operating temperature and loads, and by analogy to materials used in current production engines under similar environments.

A sketch of each scheme shown in each applicable component was generated. An index to these sketches is given in Table 10 where the schedules are categorized by scheme and component. Sketches of each scheme are shown in Figures 66 through 101.

Sketches of linkages for mechanical ACC schemes No. 5, 6A, 8, 10A, 33, and 35 are shown in Figures 102 through 107. Required actuator loads are given where appropriate.

2.5 EVALUATION CRITERIA

2.5.1 Overview

The evaluation criteria selected to rank the ACC concepts were based on LCC improvements to a new engine-aircraft design.

Component or engine efficiency improvements due to ACC result in a reduction in the size of the aircraft-engine system while still meeting the same mission and payload objectives. This approach provides the most representative evaluation of ACC because it allows the base aircraft and engine to fully incorporate the performance benefits of ACC in the design.

TABLE 10. INDEX TO SCHEME SKETCHES*

		Compressor			*Turbine*		
		Transport	*Core Engine Fighter and Transport*		*Fighter*		*Transport*
Description	*REF Scheme*	*Low*	*High*	*Seal*	*High*	*Low*	*Low*
Axial Rotor Shift	5	—	$S_{2,3,4}$*	—	$S_{2,3,4,5}$	—	—
Axial Shroud Shift	6A	S_6	$S_{7,8}$	$S_{9,10}$	—	S_{11}	S_{11}
Strap-Type Shroud	8	S_{12}	S_{13}	S_{14}	—	S_{14}	S_{14}
Screw Thread Actuated	10A	S_{15}	$S_{16,17}$	S_{18}	—	$S_{16,17}$	$S_{16,17}$
Cam Actuated	33	S_{19}	$S_{19,20}$	—	$S_{21,22}$	S_{20}	S_{20}
Pneumatic Actuated	9	S_{23}	S_{24}	—	—	S_{25}	S_{25}
Bellow Actuated	18	S_{26}	S_{27}	S_{28}	—	S_{27}	S_{27}
Movable Heatshield	35	—	S_{29}	—	S_{29}	S_{29}	S_{29}
Air Tube, Case Cool/Heat	31,22A	—	$S_{30,31}$	—	S_{32}	—	—
Heat/Cool Shroud Support	32	—	S_{33}	—	S_{34}	S_{35}	S_{35}
Heat/Cool Ring Support	38A	—	—	—	S_{36}	—	—

* "S" stands for that sketch number which shows a scheme adapted to a particular component. Sketches 1-36 appear in Figures 66 through 101. $S_{2,3,4}$ would be three sketches (No's 2, 3 and 4) which show the axial rotor shift scheme (No. 5) adapted to the HPC.

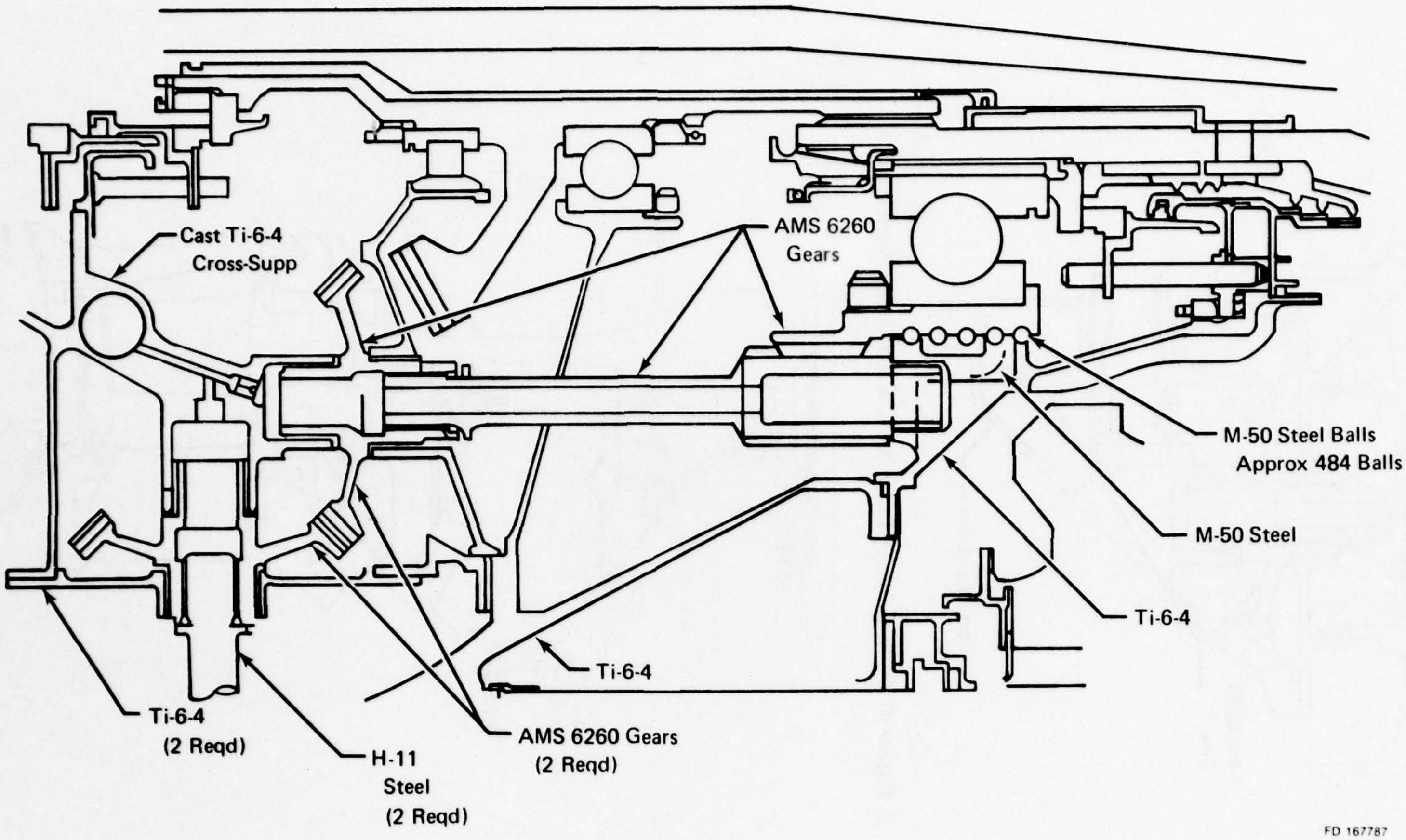

Figure 66. Rotor Shift No. 2 and No. 3 BRG Compt, Sketch No. 2

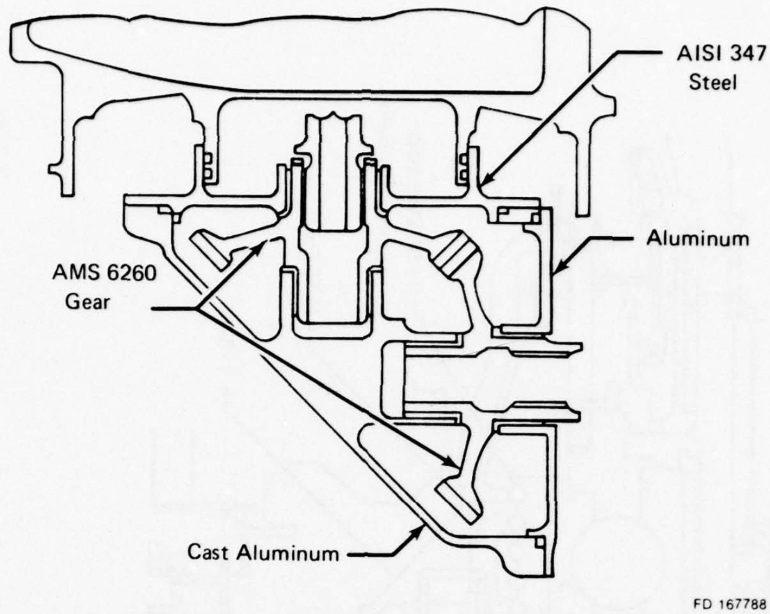

Figure 67. Scheme No. 5, Rotor Shift, Right Angle Sketch No. 3

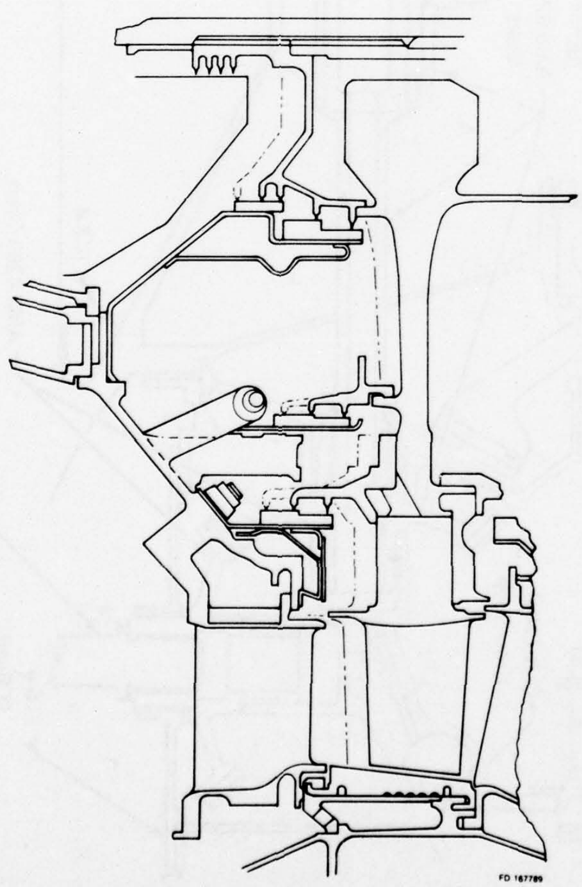

Figure 68. Turbine Rotor Shift Stages 1 and 2 Sketch No. 4

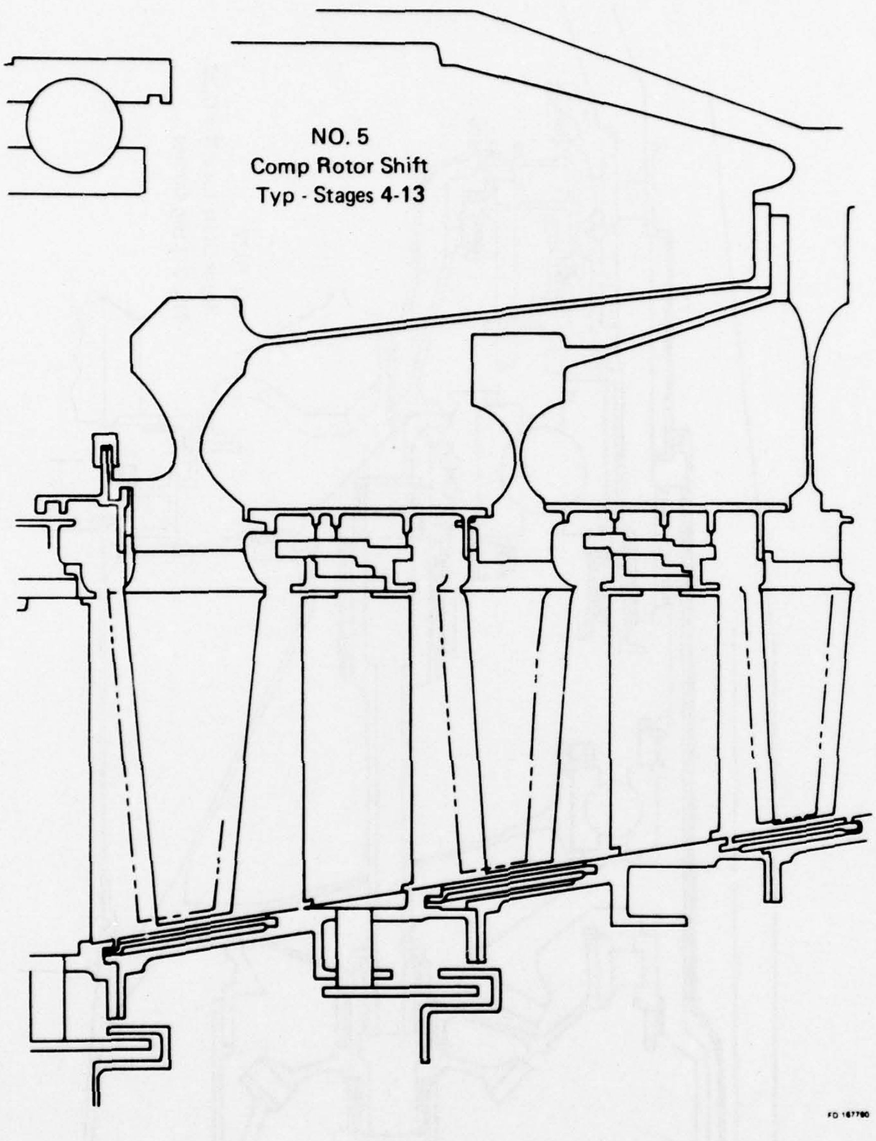

Figure 69. Scheme No. 5, Compressor or Rotor Shift, Stages 4 through 13, Sketch No. 5

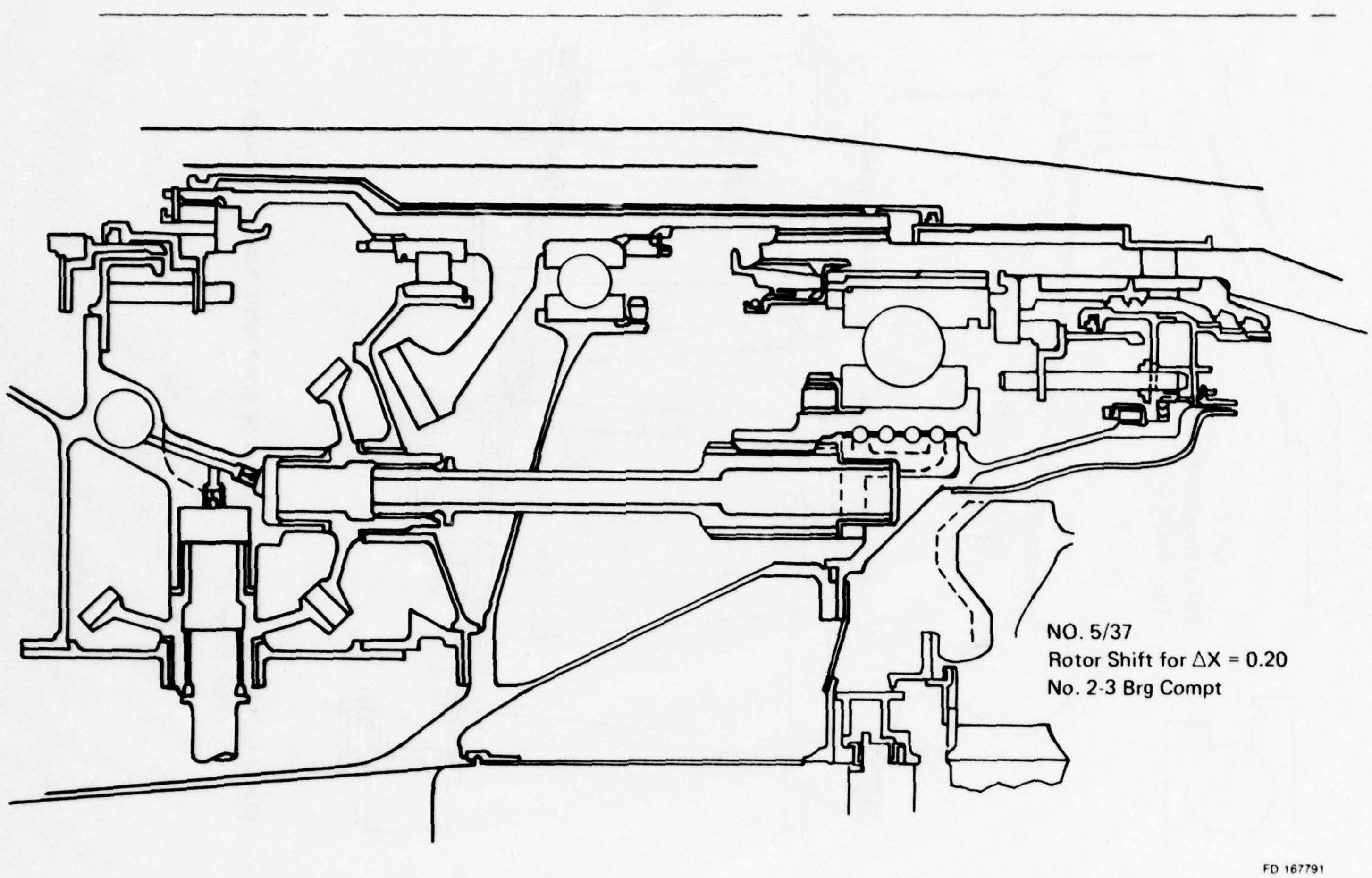

Figure 70. Scheme No. 5, Rotor Shift Sketch No. 2A

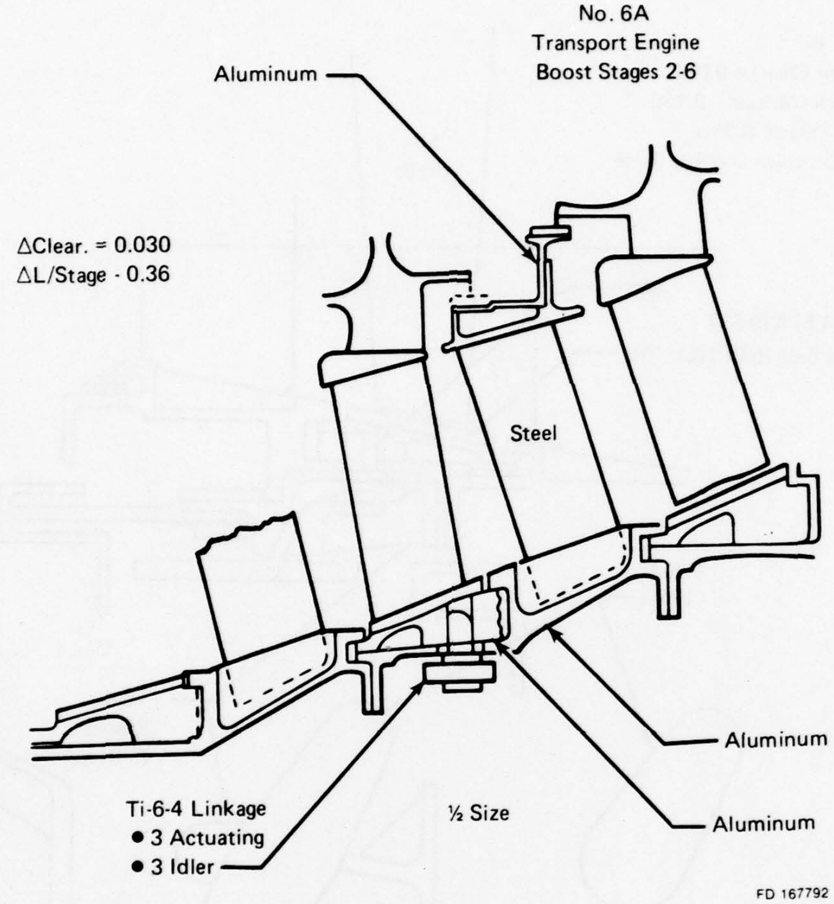

Figure 71. Scheme No. 6A, Transport Engine, Boost Stages 2 through 6, Sketch No. 6

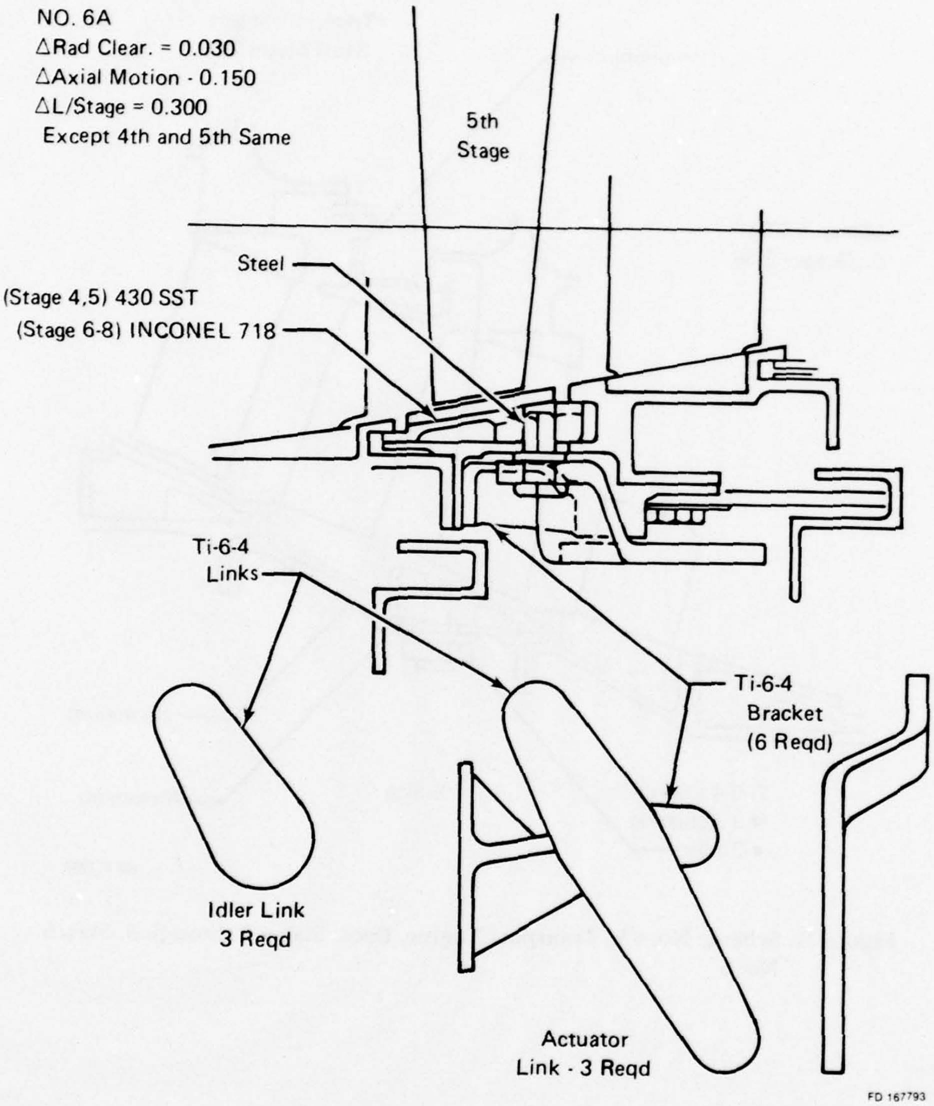

Figure 72. Scheme No. 6A, Sketch No. 6

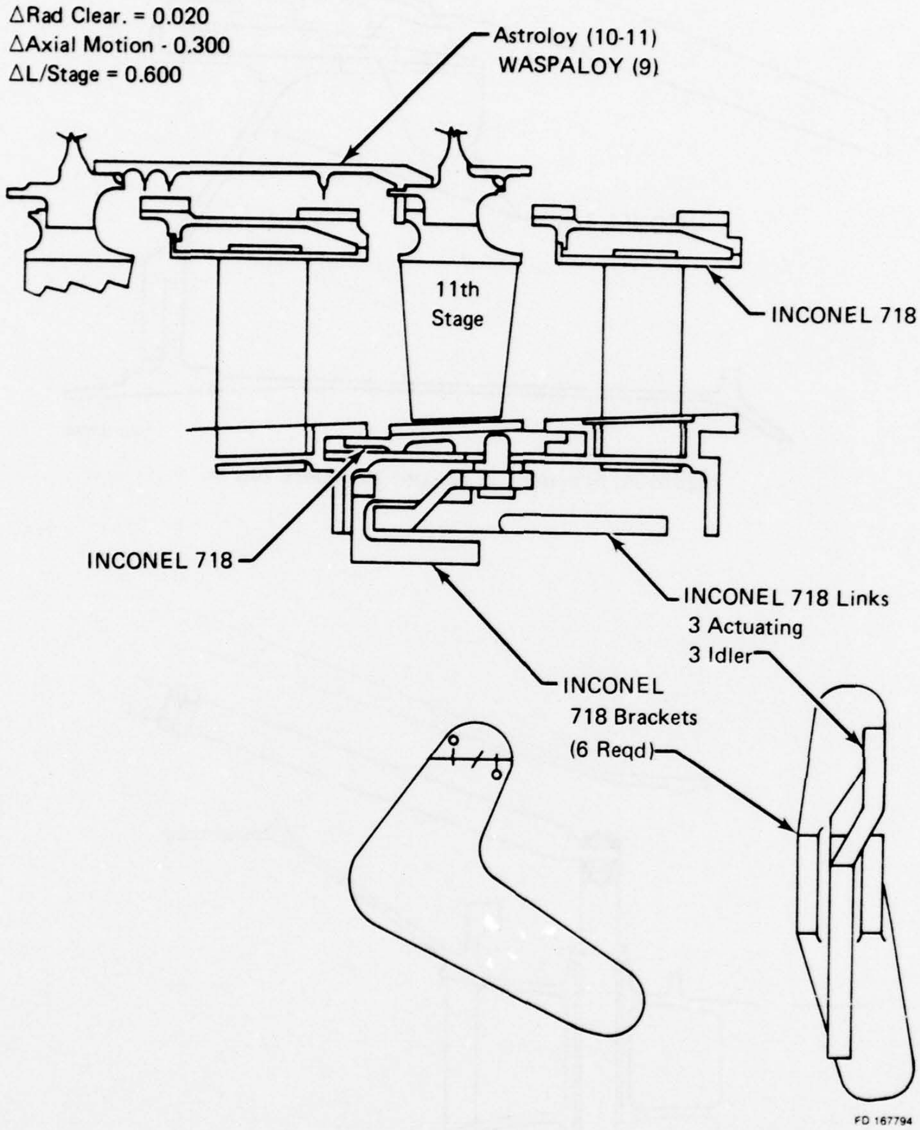

Figure 73. Scheme No. 6A, Rear Compressor Stages 9 through 11, Sketch No. 8

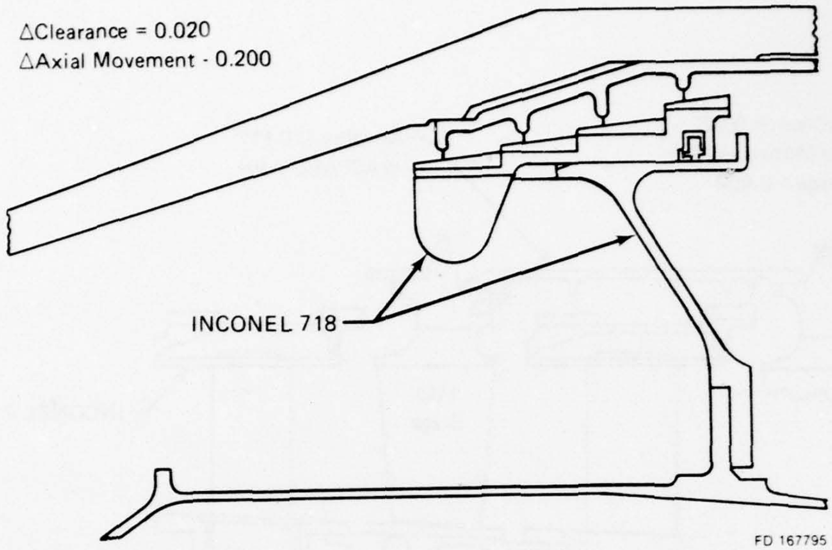

Figure 74. Scheme No. 6A and 30, Sketch No. 9

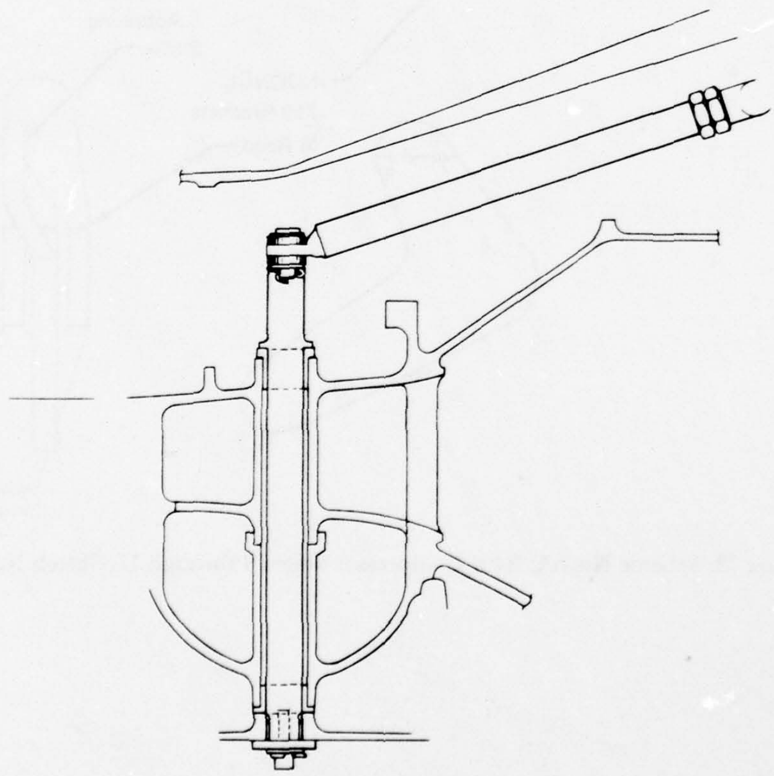

Figure 75. Scheme No. 6A, Rear Compressor Seal Linkage, Sketch No. 10

ΔRad Clear. = 0.030
ΔAxial Motion - 0.300
ΔL/Stage = 0.300

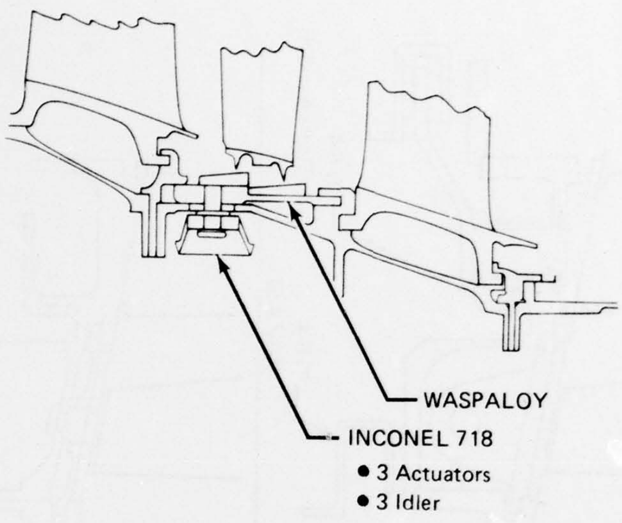

Figure 76. Scheme No. 6A, LPT, 2 Stages Sketch No. 11

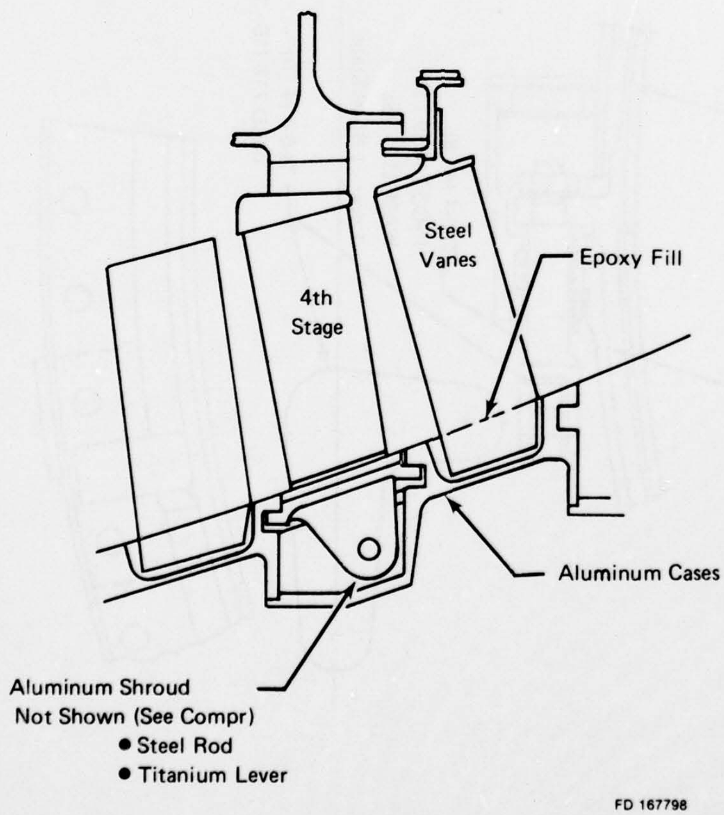

Figure 77. Scheme No. 8, Low Compressor Stages 2 through 6, Sketch No. 12

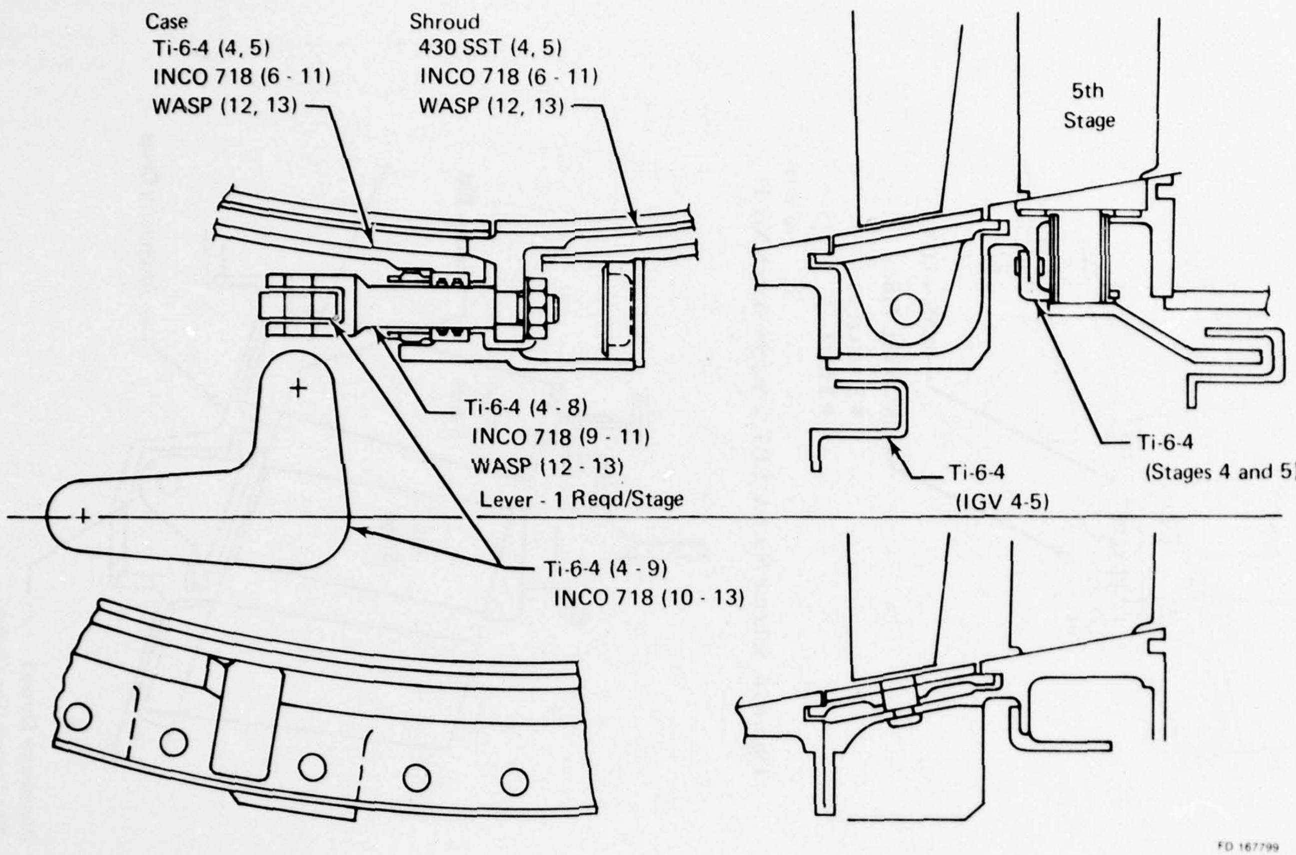

Figure 78. Scheme No. 8, Compressor Stages 4 through 13, Sketch No. 13

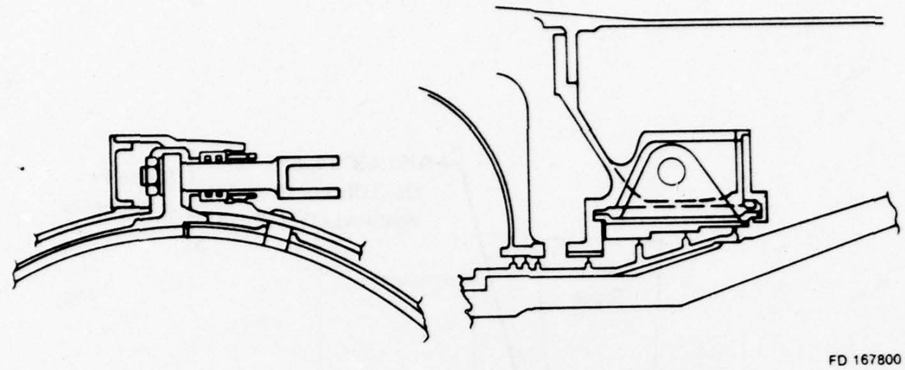

Figure 79. Scheme No. 8, Compressor Rear Seal, Sketch No. 14

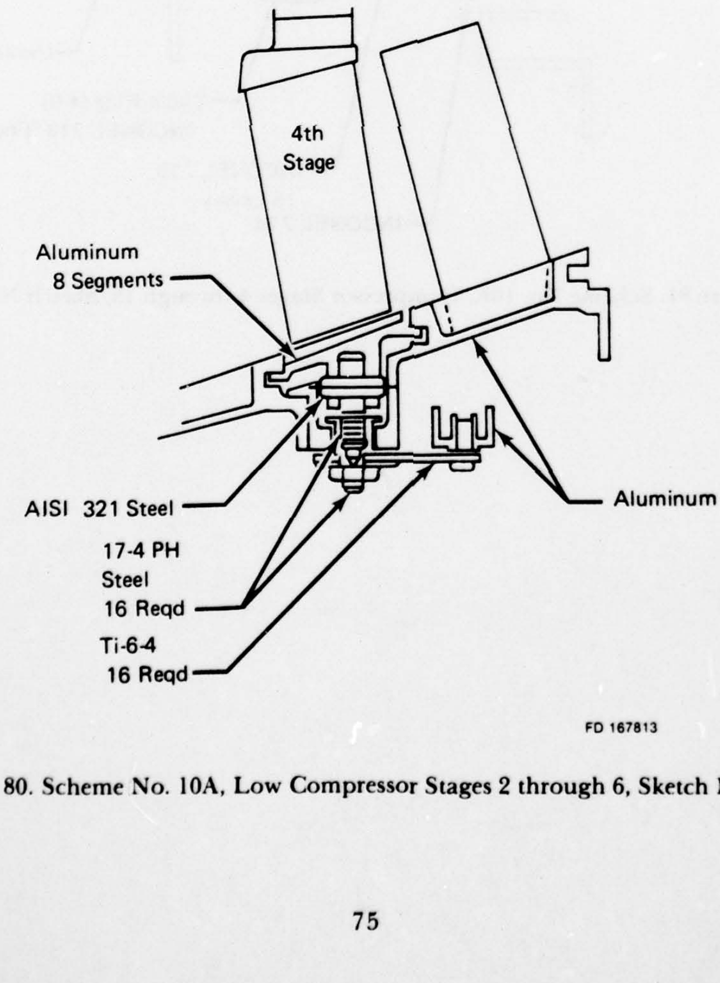

Figure 80. Scheme No. 10A, Low Compressor Stages 2 through 6, Sketch No. 15

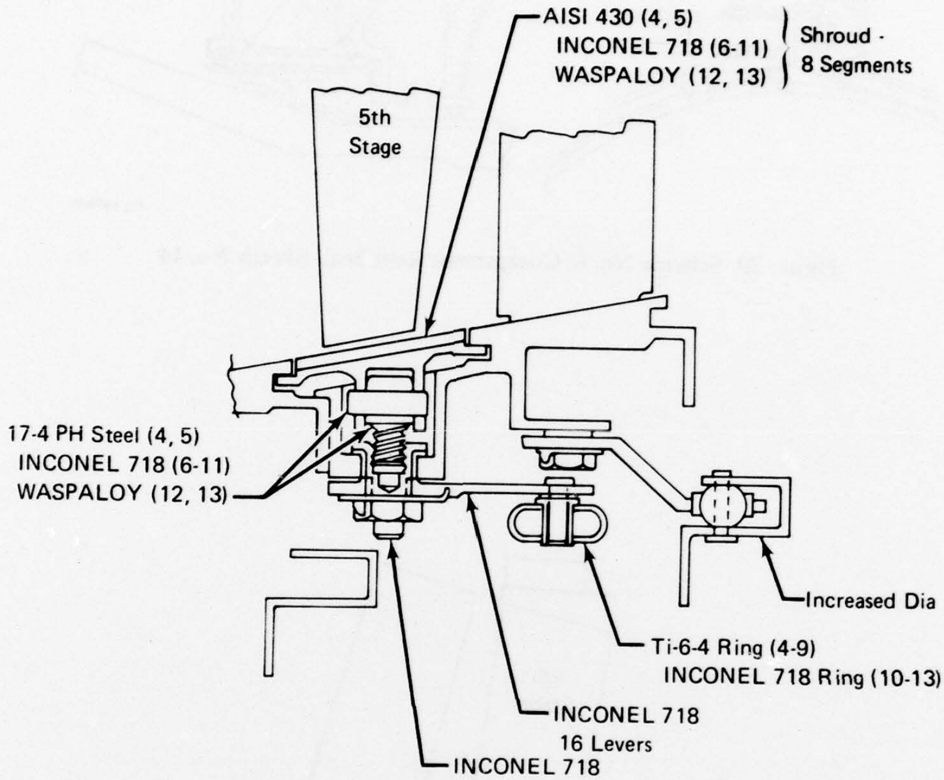

Figure 81. Scheme No. 10A, Compressor Stages 4 through 13, Sketch No. 16

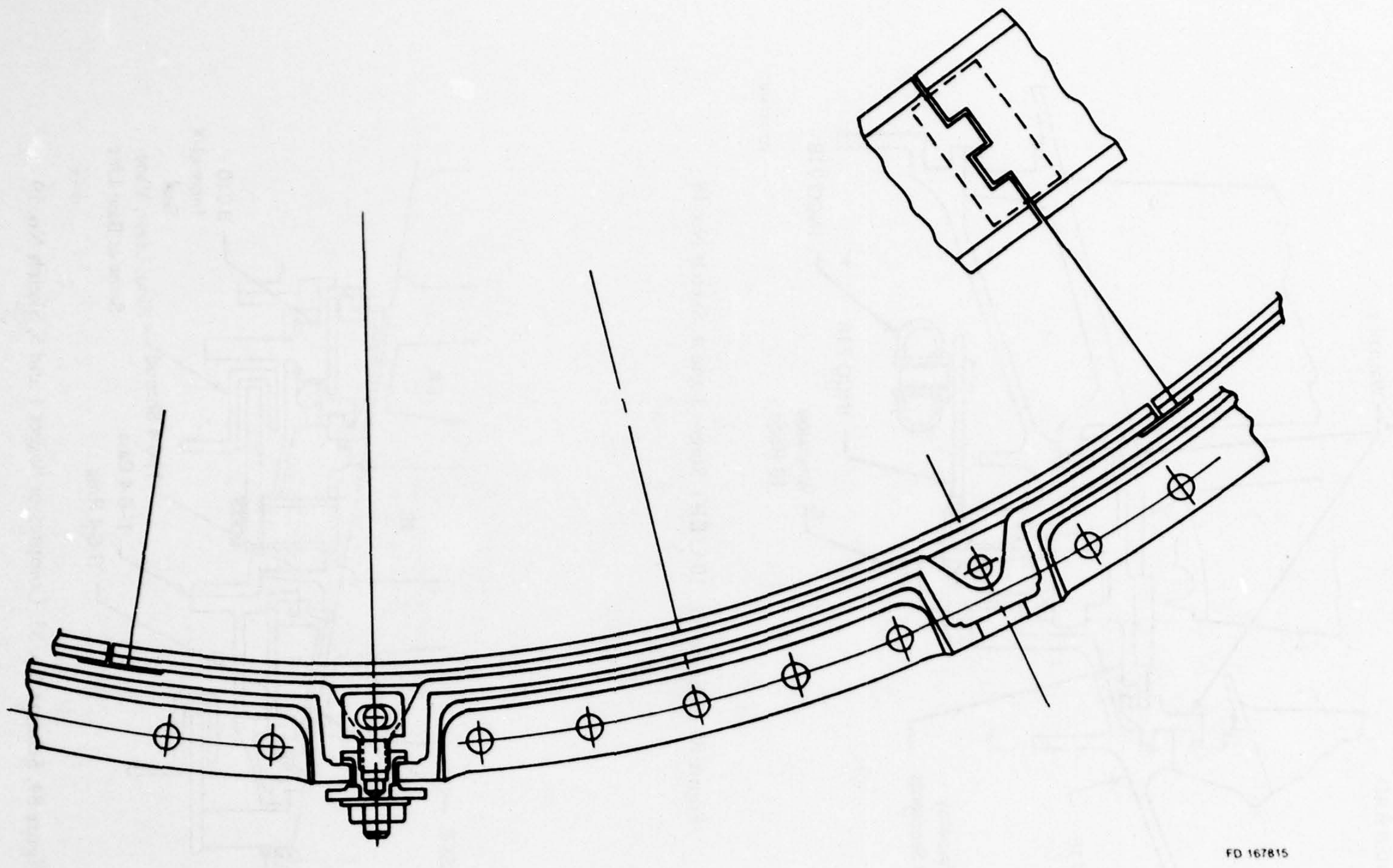

Figure 82. Scheme No. 10A, Section through 5th Stage Compressor, Sketch No. 17

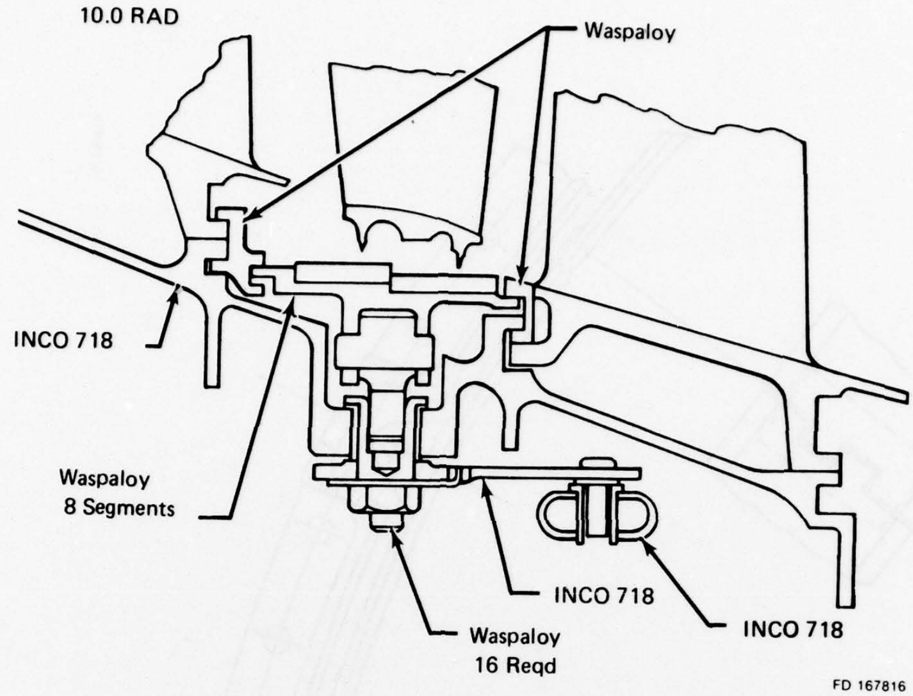

Figure 83. Scheme No. 10A, LPT Stages 3 and 4, Sketch No. 18

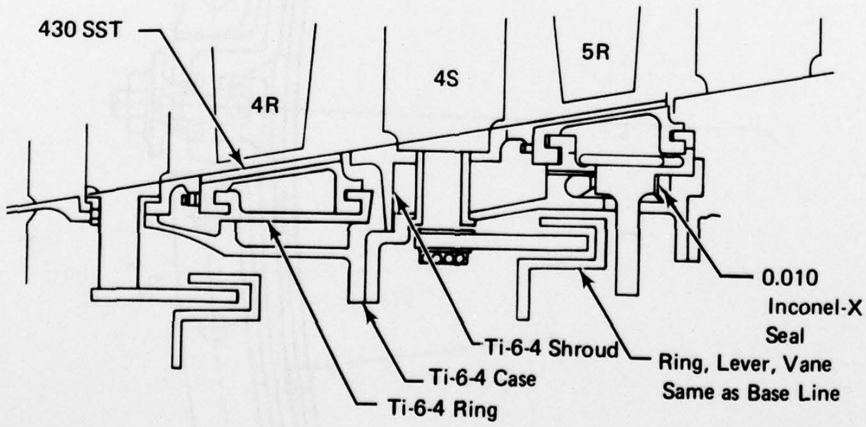

Figure 84. Scheme No. 33, Compressor Stages 4 and 5, Sketch No. 19

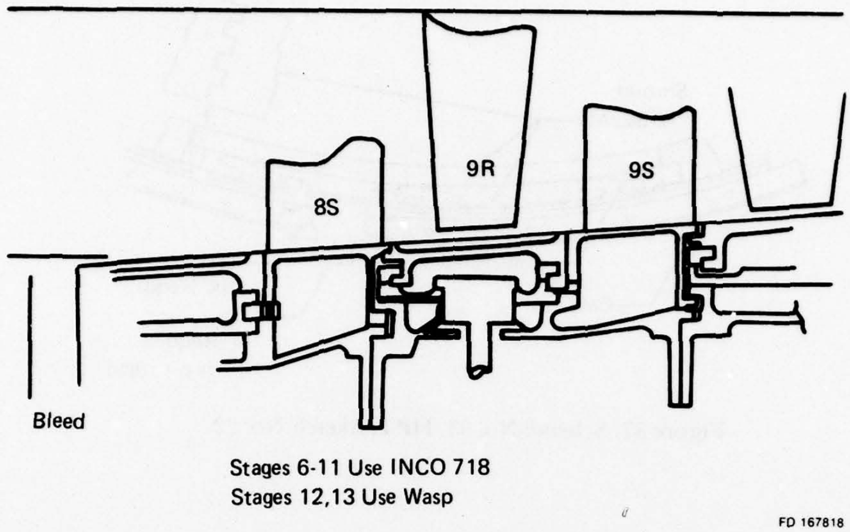

Figure 85. Scheme No. 33, Compressor Stages 6 through 13, Sketch No. 20.

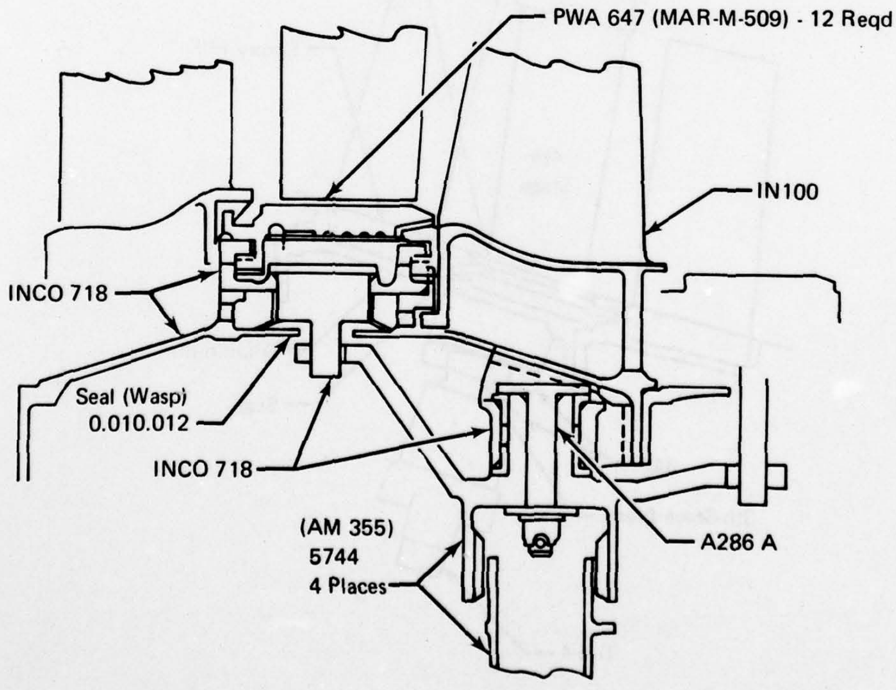

Figure 86. Scheme No. 33, HPT Stages 1 and 2, Sketch No. 21

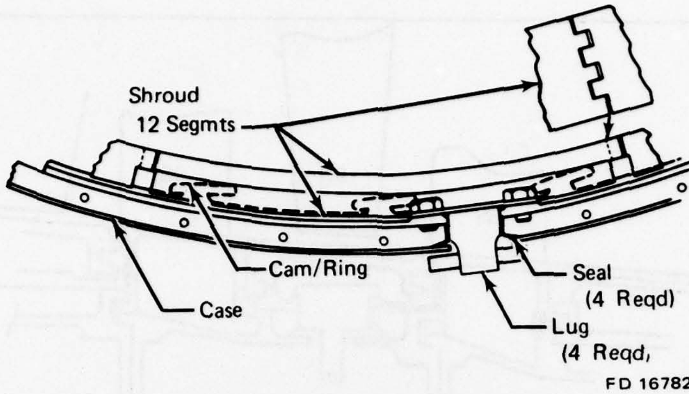

Figure 87. Scheme No. 33, HPT, Sketch No. 22

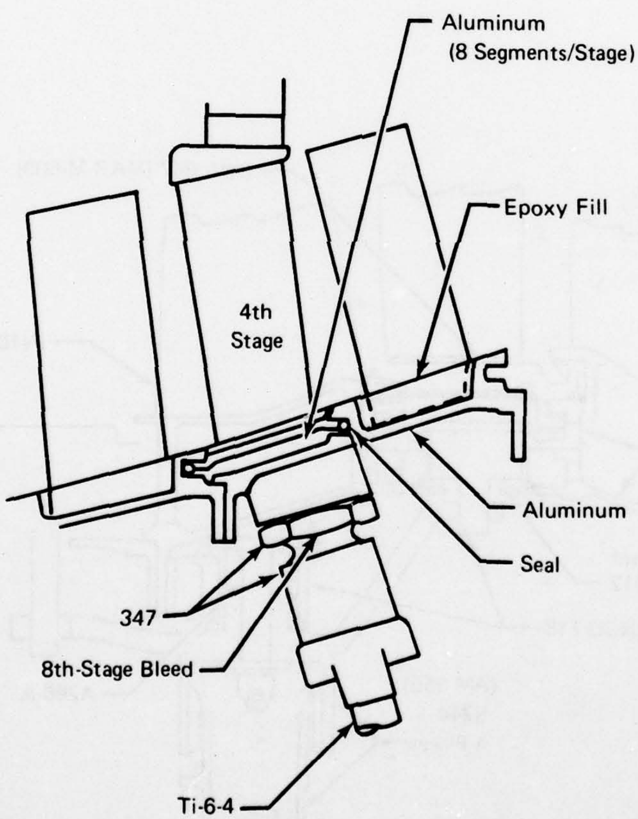

Figure 88. Scheme No. 9, Low Compressor, Sketch No. 23

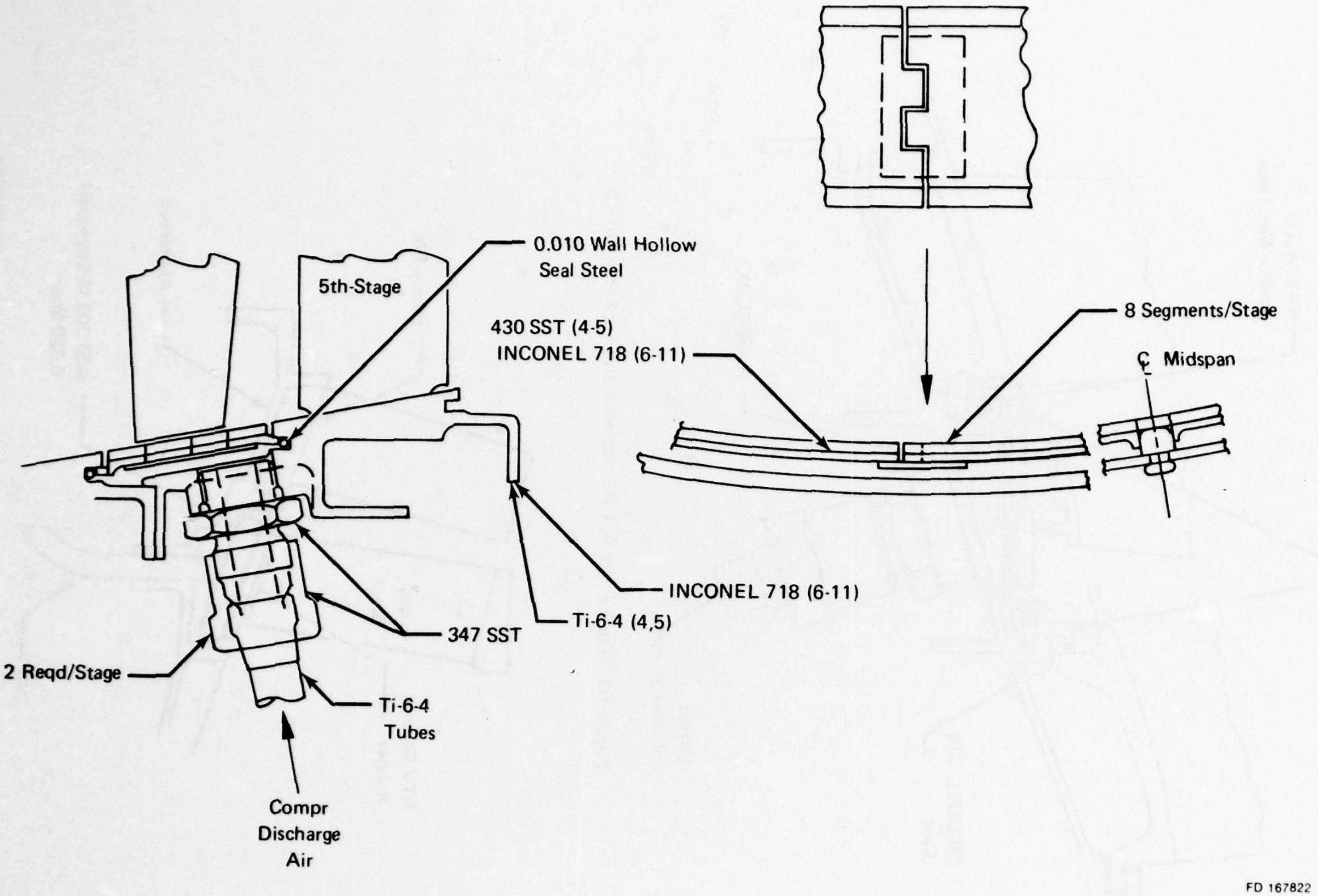

Figure 89. Scheme No. 9, Compressor, Sketch No. 24

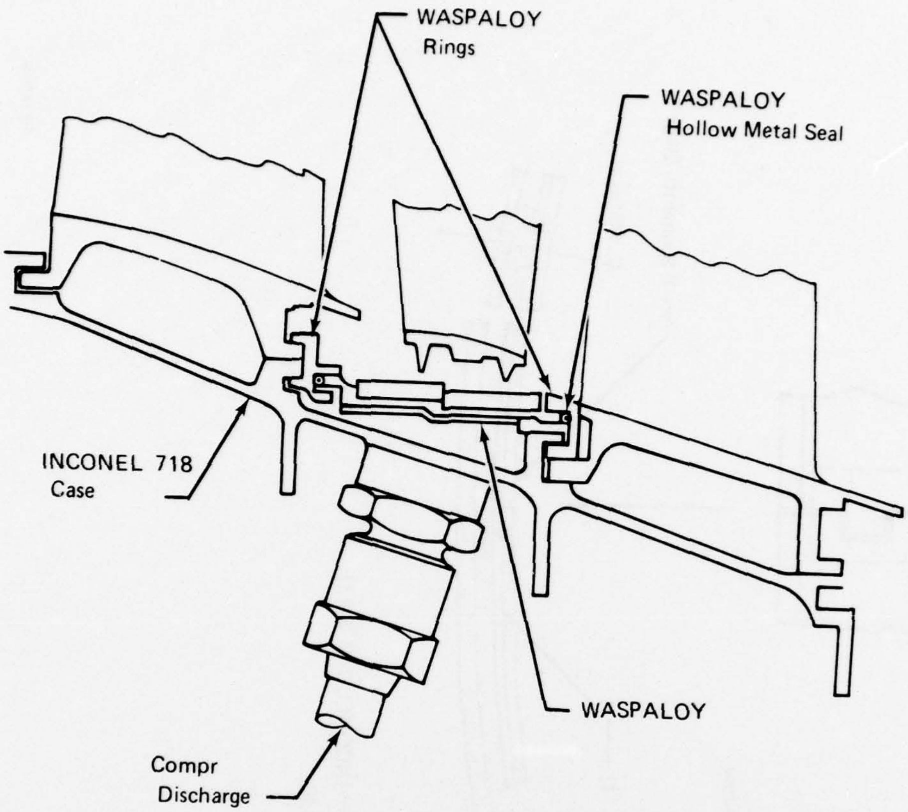

Figure 90. Scheme No. 9, LPT Stages 4 and 5, Sketch No. 25

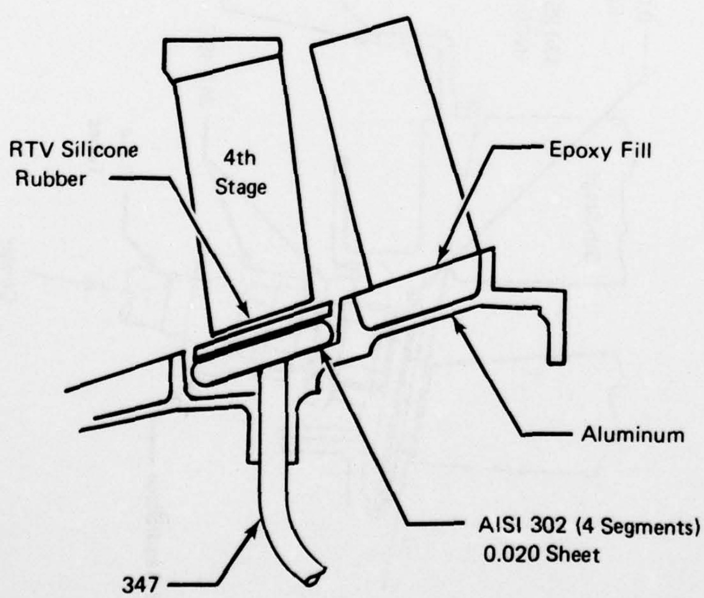

Figure 91. Scheme No. 18, Low Compressor, Stages 2 through 6, Sketch No. 26

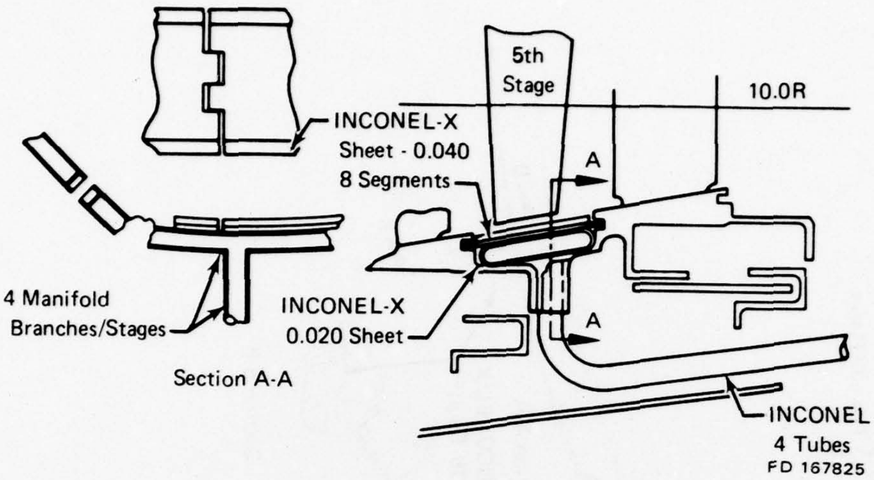

Figure 92. Scheme No. 18, Compressor, Stages 4 through 13, Sketch No. 27

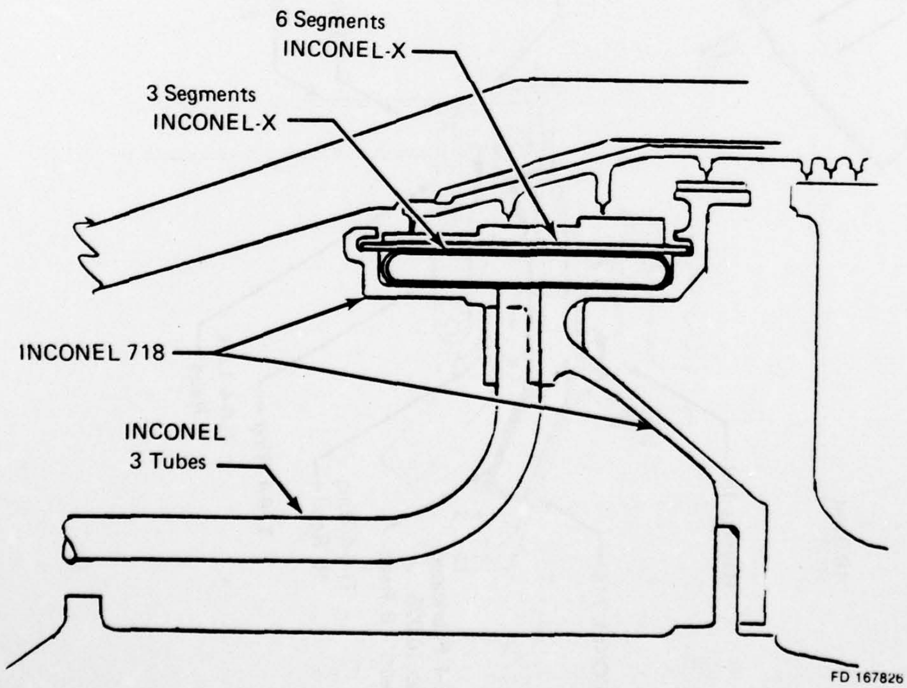

Figure 93. Scheme No. 18, Rear Compressor Seal (2 Position), Sketch No. 28

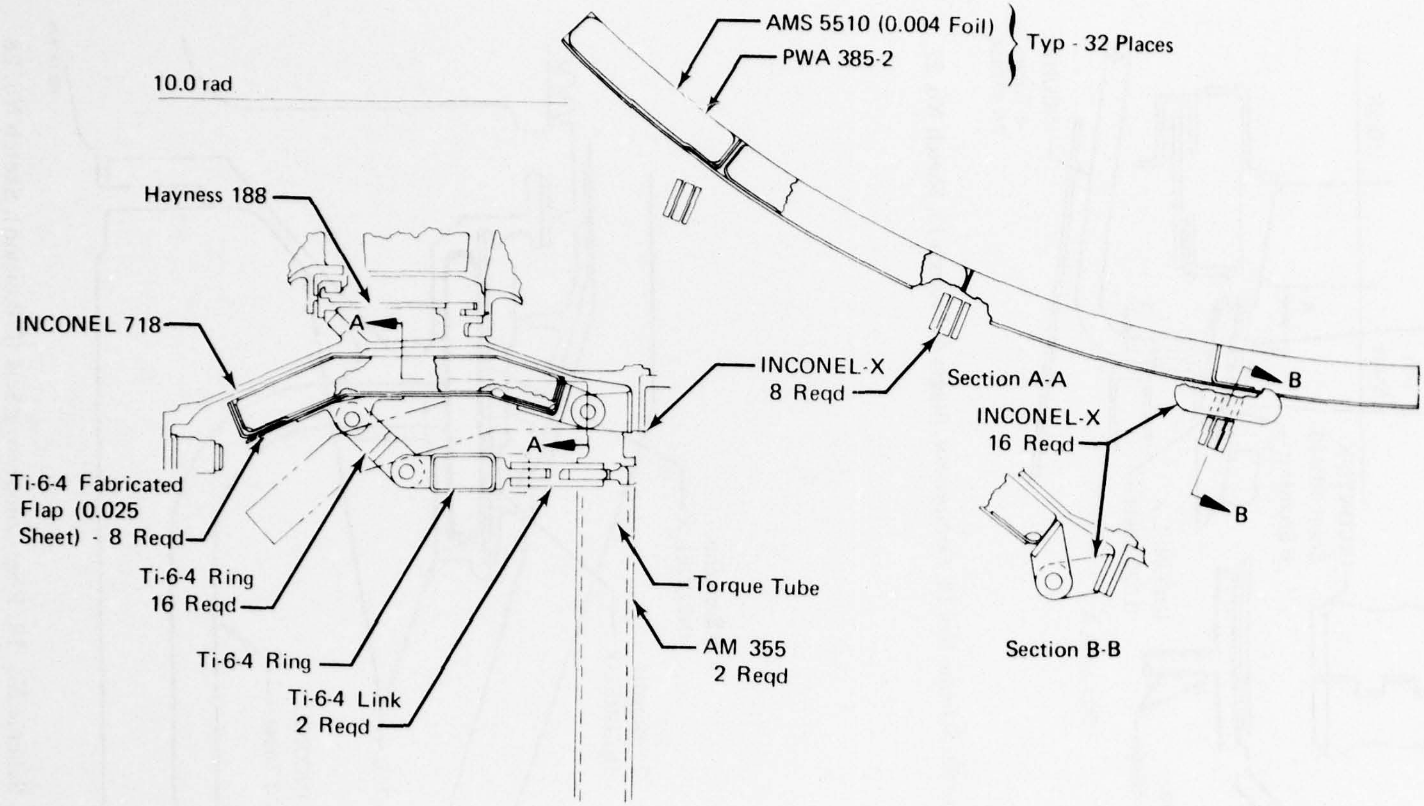

Figure 94. Scheme No. 35, Sketch No. 29

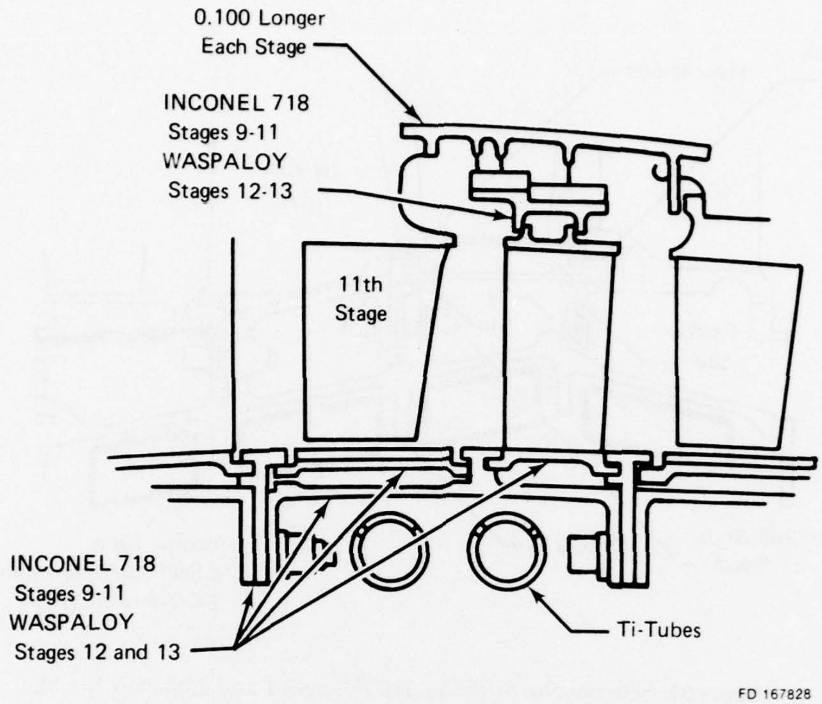

Figure 95. Scheme No. 31, Sketch No. 30

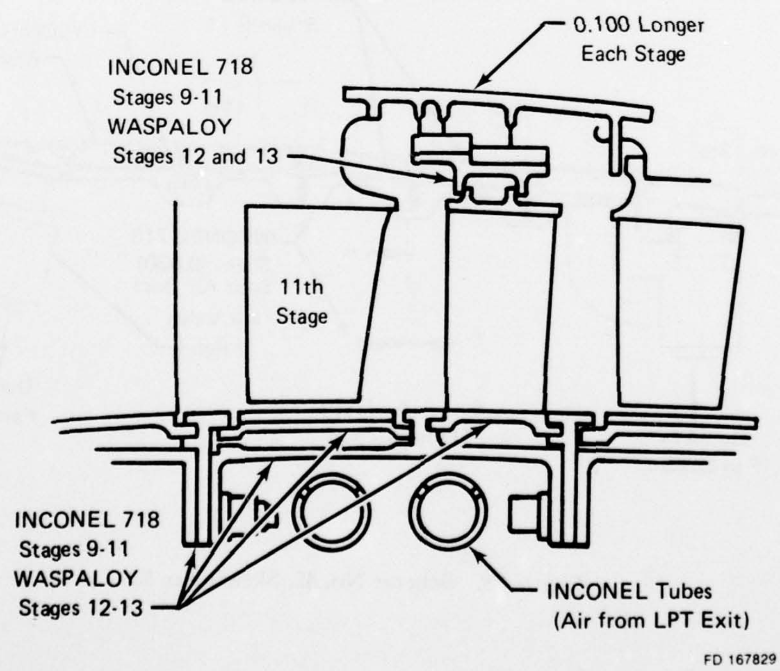

Figure 96. Scheme No. 22A, Compressor Stages 9 through 13, Sketch No. 31

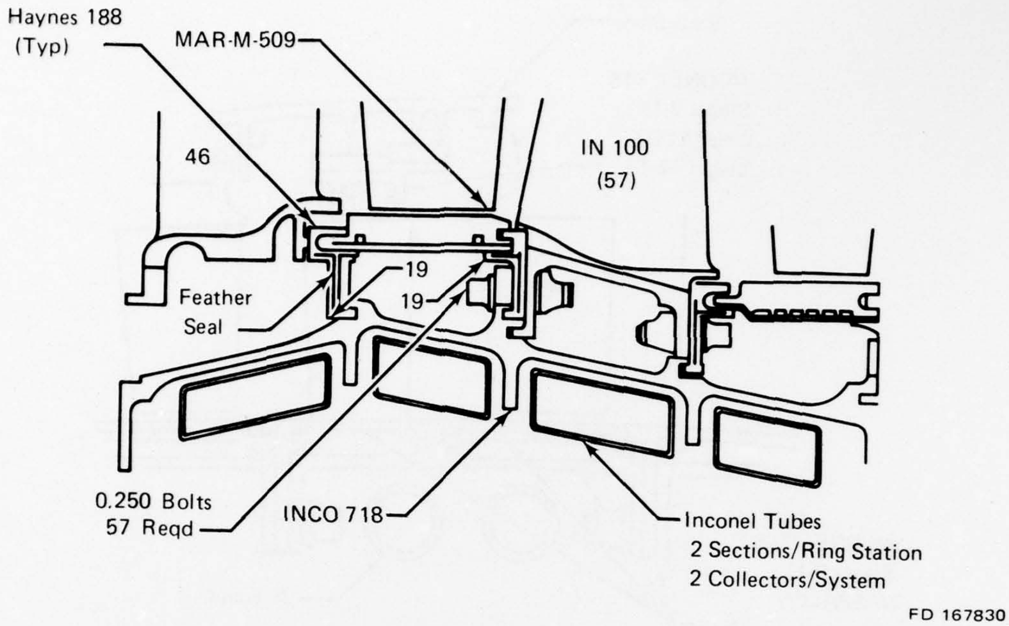

Figure 97. Scheme No. 31 (22A), HPT Stages 1 and 2, Sketch No. 32

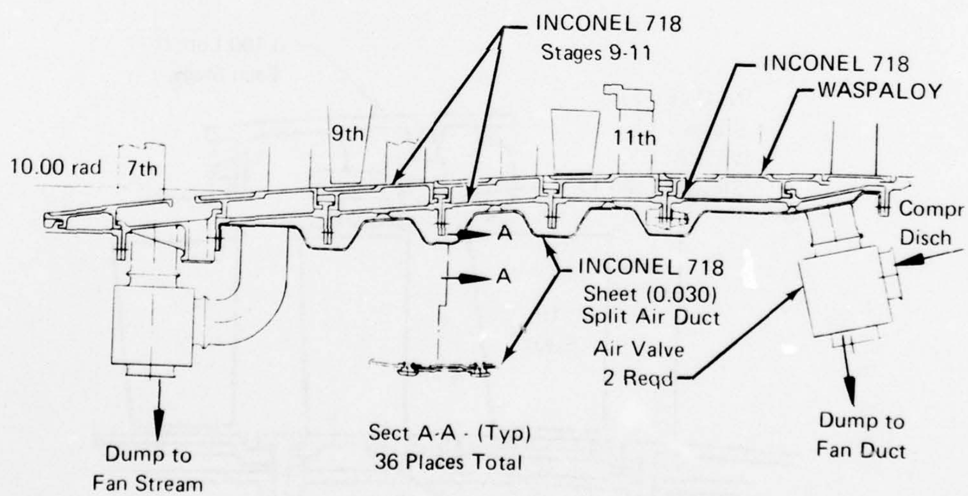

Figure 98. Scheme No. 32, Sketch No. 33

AD-A080 620 PRATT AND WHITNEY AIRCRAFT GROUP WEST PALM BEACH FL G--ETC F/G 21/5
THERMAL RESPONSE TURBINE SHROUD STUDY.(U)
JUL 79 E J KAWECKI F33615-78-C-2022
UNCLASSIFIED PWA-FR-11867 AFAPL-TR-79-2087 NL

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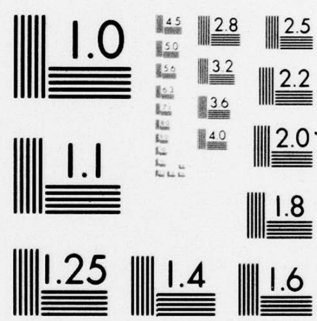


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

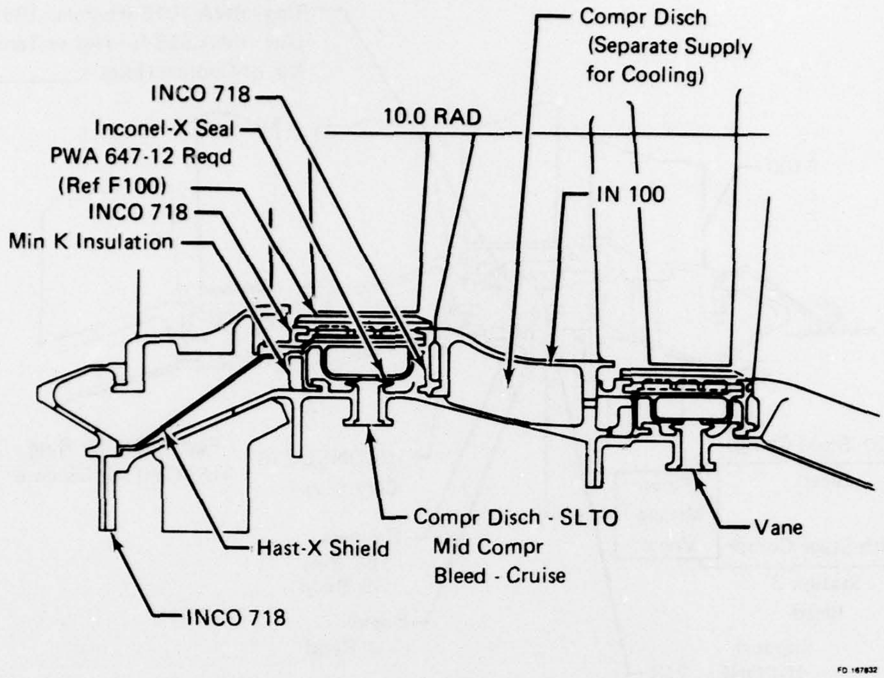


Figure 99. Scheme No. 32, HPT Stages 1 and 2, Sketch No. 34

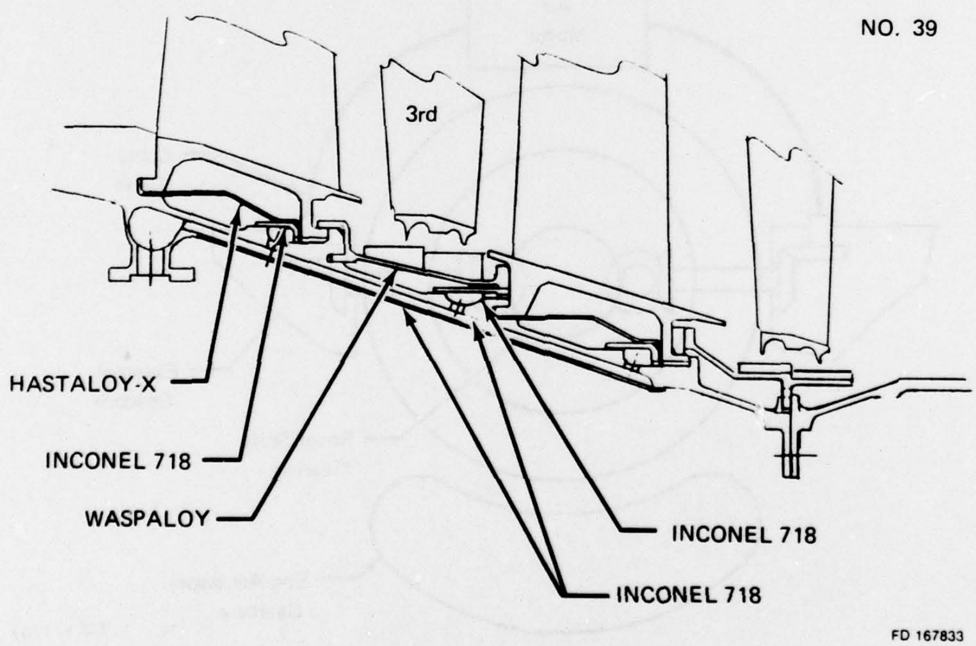


Figure 100. Scheme No. 32, LPT Stages 3 and 4, Sketch No. 35

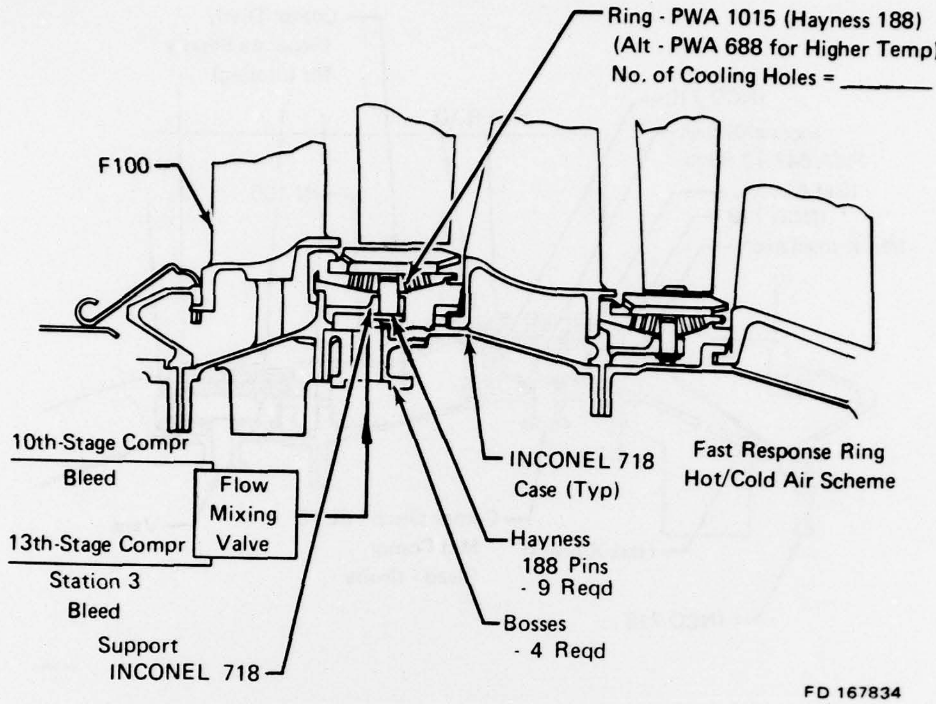


Figure 101. Scheme No. 38A, Sketch No. 36

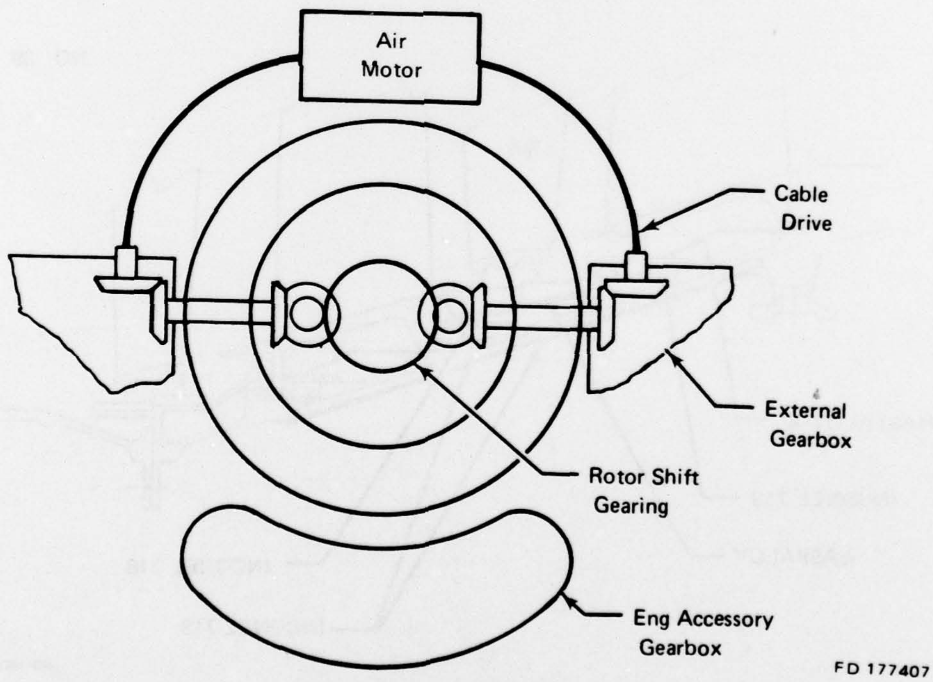
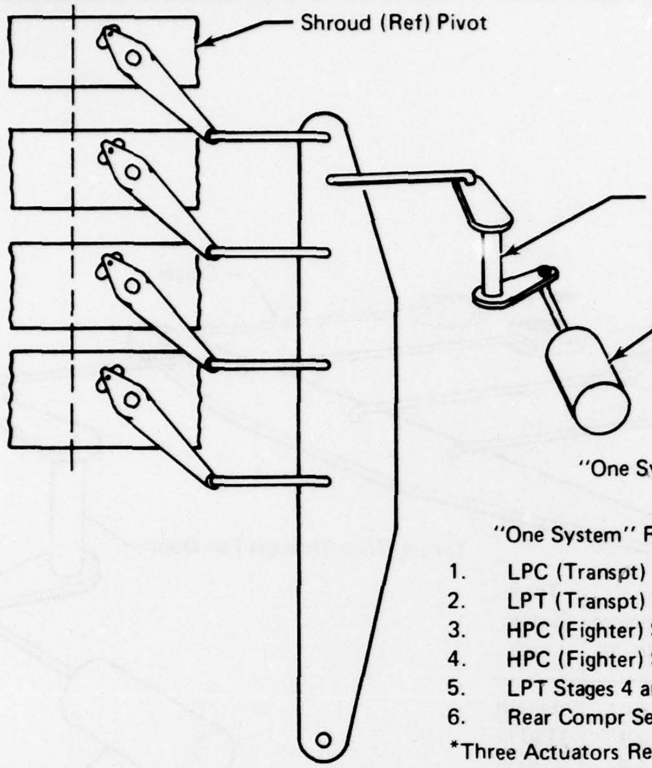


Figure 102. Linkage for Scheme No. 5



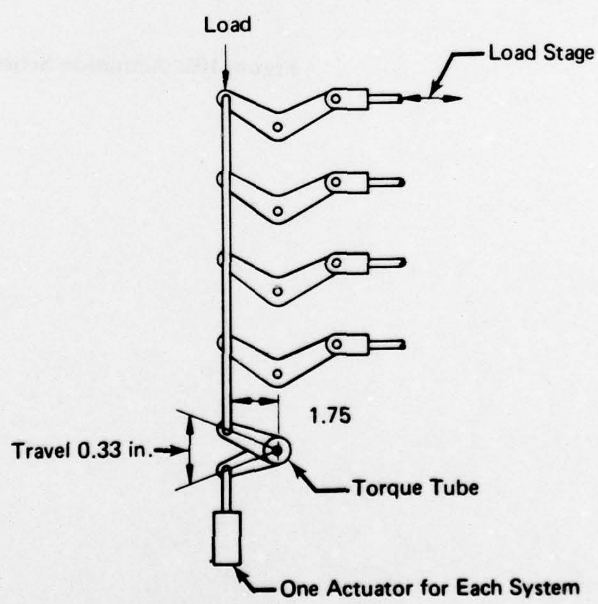
"One System" Reqd for		System Loads
1.	LPC (Transpt) 5 Stages	940 lb
2.	LPT (Transpt) 5 Stages	940 lb
3.	HPC (Fighter) Stages 4-7	750 lb
4.	HPC (Fighter) Stages 8-11	750 lb
5.	LPT Stages 4 and 5	1500 lb
6.	Rear Compr Seal*	

*Three Actuators Reqd for Rear Compr Seal

FD 167835

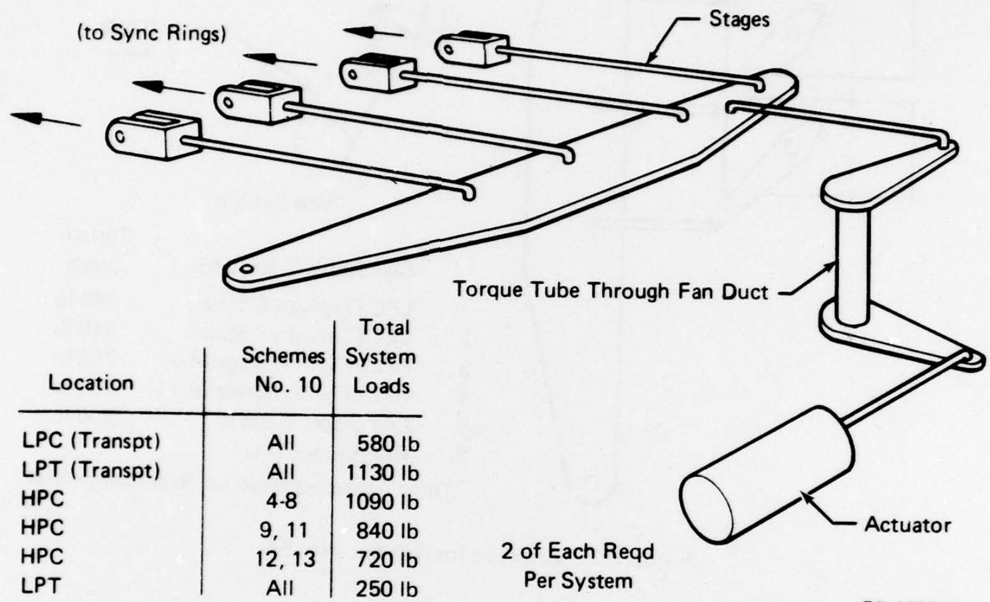
Figure 103. Linkage for Scheme No. 6A

System	System Loads
Low Press. Compr (5 Stages)	600 lb
HPC Stages 4-8	450 lb
Stages 9-11	500 lb
Stages 12,13	460 lb
Rear Compr Seal	160 lb
LPT (2 Stages)	180 lb
LPT (2 Stages) 2	910 lb
Transport (3 Stages) 3	1070 lb



FD 167836

Figure 104. Scheme No. 8



Location	Schemes No. 10	Total System Loads
LPC (Transpt)	All	580 lb
LPT (Transpt)	All	1130 lb
HPC	4-8	1090 lb
HPC	9, 11	840 lb
HPC	12, 13	720 lb
LPT	All	250 lb

Figure 105. Actuation Scheme No. 10A

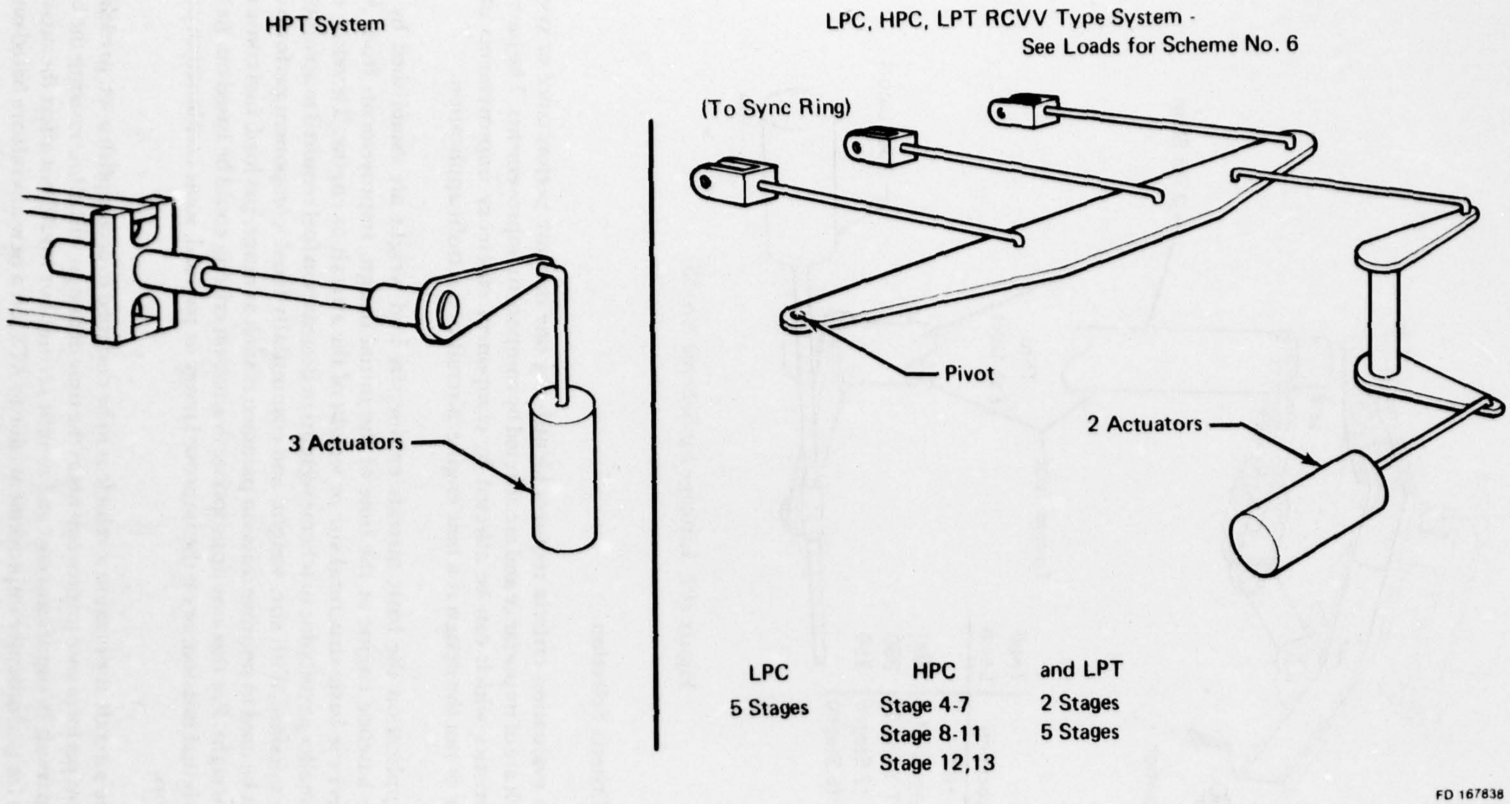


Figure 106. Scheme No. 33, Cam Actuated

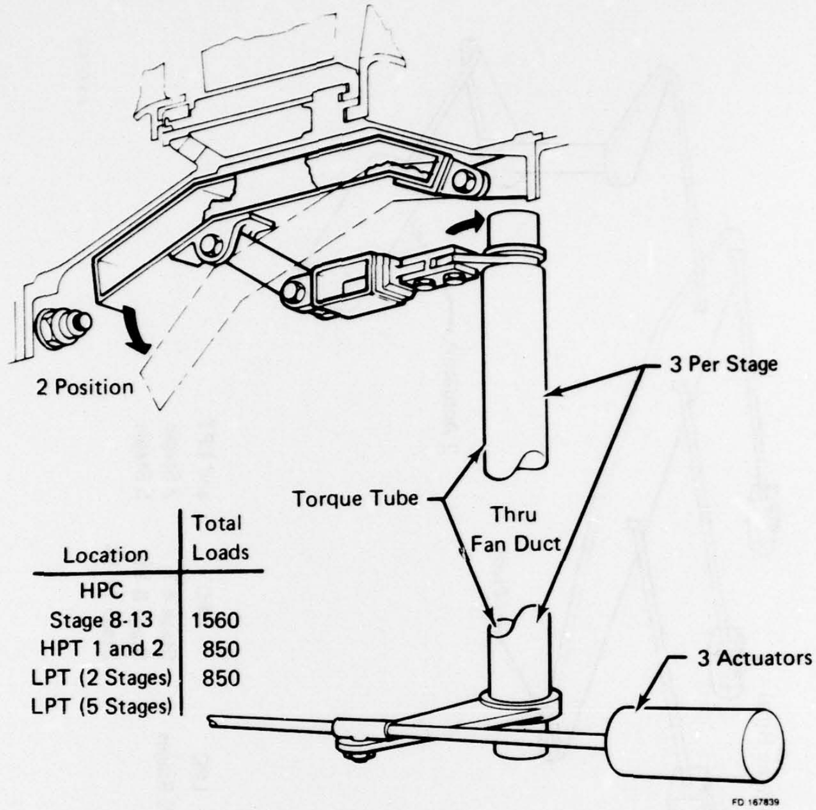


Figure 107. Linkage for Scheme No. 35

2.5.2 Evaluation Criteria Selection

Selection of an evaluation criteria requires identifying one or more performance or system characteristics which are of importance and are affected by component improvements. The particular system characteristics which can be affected by component efficiency improvements are a function of whether or not the design is a new engine/aircraft or a retrofit application.

In a retrofit application the basic aircraft/engine size and weight are established by the performance of the baseline engine at the time of the initial design. Improvements from ACC add-ons cannot affect the basic structural size or weight of the aircraft or engine. Therefore they must be limited to smaller payoffs due to scheme weights or decreases in fuel required to accomplish the original design mission. With size, weight, and cost initially fixed, component performance improvements must be used to improve mission parameters such as range, payload, fuel consumption, and thrust to weight. For this case appropriate evaluation criteria could be based on the fuel reduction for the original mission, or on the improved range or payload, some combination of the above or other factors.

In a new engine-aircraft application a vehicle is to be designed to accomplish a set, predefined mission. Component performance improvements at the time of design will allow resizing the basic vehicle. This would result in significant cost and weight savings but would not affect the mission. Evaluation criteria for performance improvements due to ACC on a new aircraft are based on the resulting engine and aircraft weight and size reductions alone.

The significant differences between the type and degree of expected payoffs that are created by the two different potential applications (new engine vs retrofit) require that the application be determined before the evaluation criteria are defined. Consistent with the program objective of evaluating ACC on advanced engines, it was determined that the most representative evaluation would result from considering clearance improvements on a new design for a fixed mission. To evaluate ACC on a retrofit application would unfairly penalize the concept because of the reduced payoff and the additional expense of redesigning and replacing existing hardware. By comparison, application to a new engine allows the full potential of the ACC benefits to be realized by resizing the vehicle to the new efficiency level and allowing overall integration into the system.

For the new engine application where the mission and performance are fixed, only the system size, weight, and cost are affected by improvements due to ACC. The most representative measure available to compare changes in these different areas is LCC. This parameter accounts for not only the engineering, development, and procurement costs, but also for the system size and effectiveness changes caused by added weight and the long term maintenance and reliability costs of operating the engine and aircraft.

2.5.3 LCC Assessment

The overall LCC approach is summarized in the following steps:

1. Calculate the Baseline Weapon System LCC for each of the two applications.

2. Generate trade factors for system LCC vs engine weight and TSFC using mission analysis models.

3. Calculate the incorporation cost increase from the baseline for each concept using detailed weight, cost, reliability and maintainability assessments, and the LCC Worksheet (Figure 108) to assure consistency.

4. Determine the performance benefit for each scheme using the trade factors generated in step (2) and analytically calculated clearance improvements.

5. Combine incorporation costs and performance benefits to determine the net LCC change.

The models and methodology used to perform the above steps are discussed below.

2.5.4 Active Clearance Control LCC Worksheet

An Active Clearance Control LCC Worksheet was prepared to facilitate the screening of a large number of potential schemes for the two applications (Figure 108). This worksheet was used to calculate the ΔLCC from the fighter and transport baseline LCC for each concept. A brief description of each section on the worksheet is given in the following section, along with a worked example in Figure 108.

Engine Development ΔCost. The additional development cost to qualification is calculated using the number of equivalent engines to Qualification Testing (QT) approach. The number of equivalent experimental engines used in the formula varies with each application and the development cost increase is proportional to the acquisition cost increase. There are 120 equivalent engines to QT for the transport, and 150 for the fighter.

Unit 7 Scheme 20 BY ____

☐ Fighter
☒ Transport

Concept: Air Tube Case Cooling
Stages: Fan ____ HPC ____ HPT 1&2 LPT ____

		Totals		Col on Table 15
I	Engine Development ΔCost (Baseline Size) / Cost to QT = (5) (Eq Exp Eng) (ΔCost) = (5) (120) (3406) = + $	2.044	M	I

II Engine Acquisition ΔCost (Baseline Size)

No. Stages		Case		ΔCost/Stage Linkage		Controls		Total Cost
2	X(		+	1338	+		) =	2676
	X(		+		+		) =	
	X(		+		+		) =	
	X(		+		+		) =	

Other ____

1.3(1272 Engines) .98 X$ 3476 = + $ 5.633 M II

III Engine Maintenance Cost (Baseline Size)

Part Name	B/D	Δλ/10⁶		% Discard		Cost		$/MEFH
			X		X		=	
Case	D	36	X		X	268	=	9648.
Tubing	B	15	X		X	772	=	11580
			X		X		=	
			X		X		=	
			X		X		=	
			X		X		=	
			X		X		=	
			X		X		=	
Controls	B	77	X		X	100	=	7700

Total Spare Parts = 1.5 (.98) (14.336 MEFH) X $ 28928. = + $ .610 M

Base Labor = (λB 92) (14.336 MEFH) (97. MMH) ($16) = + $ 2.047 M

Depot Labor = (λD 36) (14.336 MEFH) (226 MMH) ($26) = + $ 3.033 M

5.69 M III

IV ΔWeight Effect on Aircraft

(.98) (34.2 lb/eng) ($ .146 M/lb) = $ 4.89 M

VI Performance Effect on Aircraft

(1.1 0.1 in.) ($50.5 M/.01 in.) = $ 55.6 M

NOTES:

IV. LCC SUMMARY

		ΔLCC		
Engine Development	+ $	2.044	M	I
Engine Acquisition	+ $	5.633	M	II
Engine Maintenance	+ $	5.690	M	III
Parts	+ $	.610	M	
Base Labor	+ $	2.047	M	
Depot Labor	+ $	3.033	M	
Aircraft Weight Effects	$	4.890	M	IV
Incorporation Cost	+ $	18.257	M	V
Aircraft Perf Effect	- $	55.55	M	VI
Weapon System Total	- $	37.293	M	VIII

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Figure 108. Life Cycle Cost Worksheet

Engine Acquisition ΔCost. Standard manufacturing costs for each scheme were calculated on a "per stage" basis. In this section, the case, linkage, and control costs were combined and adjusted by a factor of 1.3 to account for overhead costs and profit.

The cost and weight estimates for each scheme were based on hardware sized for the base engines. The study engines were scaled to meet thrust requirements, and scaling factors were applied to all cost and weight values to adjust for the correct baseline flow size. These factors are included in Table 11. For the given example, the cost of $1338 per stage is taken from Table 17, Cost Data (Summary).

TABLE 11. ACC LIFE CYCLE COST GROUND RULES

	Application	
	Fighter	*Transport*
Life cycle, years	12	20
Number of aircraft	720	256
Flight hours/year/aircraft	300	700
Engines per aircraft	1	4
Life cycle engine flight hours, millions	2.592	14.336
Total engine quantity	1137	1282
Experimental engine cost/production cost	5.0	5.0
Development cost to QT, equivalent experimental engines	150	120
Engine price/cost ratio	1.3	1.3
Spare parts price/cost ratio	1.5	1.5
Base level labor rate, $/MMH	$16.00	$16.00
Depot level labor rate, $/MMH	$26.00	$26.00
Size scale factor, baseline/F100	1.33	0.95
Weight scale factor, baseline/F100	1.15	0.98
Cost scale factors, baseline/F100	1.12	0.98

Engine Maintenance ΔCost. Failure rate ($\Delta\lambda$) and required replacement time estimates were combined with labor and parts cost to determine maintenance costs. The failure rates are shown in Table 12 and the average maintenance hrs per scheme in Table 13.

Labor costs were calculated separately for items replaced at the base and depot maintenance levels. A labor rate of $16.00 per maintenance manhour (MMH) was used at the base level and $26.00 per MMH at the depot level.

ΔWeight Effect on Aircraft. The additional engine weight resulting from the incorporation of ACC hardware results in an increase in aircraft TOGW and therefore system ΔLCC. Trade factors relating aircraft TOGW to system ΔLCC were applied to the engine weight change for each scheme and each mission to determine the LCC increases due to ACC weight changes. The weight increase for each scheme is given in Table 14, and the weight to LCC trade factor is given in Table 21.

Performance Effect on Aircraft. The effect of improved clearances on performance (hence LCC) were generated for each engine application. The clearances are given in Table 6, and the clearance to ΔLCC trade factor in Table 20.

Combining the cost of development, acquisition, maintenance, weight and performance gives the net LCC savings/penalty for each of the ACC schemes. This is done in the lower right hand corner of the worksheet, where each subtotal is taken from the appropriate previous section. Included are the effects on the aircraft as well as the engine. The total weapon system ΔLCC was then used to rank the individualschemes in order of payoff.

TABLE 12. ACC SYSTEM RELIABILITY ($\Delta\lambda$/1000 FLIGHT HR) FOR FIGHTER AND TRANSPORT

		Base*	Depot**
5	Axial Rotor Shift	139	96
8	Strap Type Shroud	236	89
6A	Axial Shroud Shift	217	180
9	Pneumatic Segmented Shroud	170	129
10A	Screw Thread	213	179
18	Bellows Actuated Shroud	45	293
31	Air Tube Case Cool	82	0
32	Heated and Cooled Support	154	160
22A	Air Tube Case Heating	158	0
33	Cam Actuated Shroud	200	145
35	Movable Heatshield	222	32
38A	Heated/Cooled Ring	200	175

*Failure rate of items capable of being repaired at the base level
**Failure rate of items which must be repaired at the depot level

TABLE 13. MAINTENANCE TASK TIMES FOR ACC SCHEMES (IN DIRECT MAINTENANCE MAN-HOURS (MMH))

Scheme No.	Scheme Name	Avg Hours for Removal and Replacement of Each Part: Base Repairs	Depot Repairs
5	Axial Rotor Shift	100	200
6A	Axial Shroud Shift	106	236
8	Strap Shroud	102	229
9	Pneumatic Segmented Shroud	95	223
10A	Screw Thread	103	231
18	Bellows Actuated Shroud	97	228
31	Air Tube Case Cooling	97	—
32	Heated and Cooled Supports	97	231
22A	Air Tube Case Heating	97	—
33	Cam Actuated Shroud	106	237
35	Movable Heatshield	106	237
38A	Heated/Cooled Ring	94	157

TABLE 14. ACC WEIGHT SUMMARY ACC COMBINATIONS

Unit/ Scheme	Description	Section	Stages	Case Mod Wt	Linkage Mod Wt	Controls Wt	Total Wt	Driver % of Total w/o Control
6A	Axial Shroud Shift	HPC	6-9	9.9	13.5	10	33.4	Sync ring bracket 25%
6A	Axial Shroud Shift	HPC	10-13	18.4	14.3	10	42.7	stage length 40%
	Axial Shroud Shift	LPT	3-8	5.8	5.0	10	20.6	Sync ring 15%
8	Axial Shroud Shift	Rear Comp	Seal	2.5	6.0	10	18.5	
8	Strap Type Shroud	HPC	6-9	1.0	1.2	10	12.2	Housing 16%
8	Strap Type Shroud	HPC	10-13	1.7	1.6	10	13.3	
	Strap Type Shroud	LPT	3-8	2.2	2.0	10	14.1	
9	Strap Type Shroud	Rear Comp	Seal	0.4	0.6	10	11.0	
9	Pneumatic Seq Shroud	HPC	6-9	1.3	5.1	3	9.4	
9	Pneumatic Seq Shroud	HPC	10-11	0.7	2.6	3	6.3	
	Pneumatic Seq Shroud	LPT	3-8	0.9	3.3	3.0	7.2	
10A	Screw Thread ACT Shroud	HPC	6-9	7.1	12.8	10	29.9	Sync ring 35%
10A	Screw Thread ACT Shroud	HPC	10-13	7.1	12.8	10	29.9	Lever 25%
	Screw Thread ACT Shroud	LPT	3-8	8.9	16.0	10	34.9	Bosses 25%
18	Bellows ACT Shroud	HPC	6-9	2.4	8.2	15	25.6	
18	Bellows ACT Shroud	HPC	10-13	2.4	8.2	15	25.6	Bellows 35%
	Bellows ACT Shroud	LPT	3-8	3.0	10.2	15	28.2	Tube 20%
31	Bellows ACT Shroud	Rear Comp	Seal	2.3	0.7	15	18	Sheet 35%
31	Air Tube Case Cooling	HPC	10-13	9.9	10.4	7	27.3	Manifolds 35%
31	Air Tube Case Cooling	HPT	1-2	3.0	24.2	7	34.2	Feed Tubes 25%
32	Heated and Cooled Spts	HPC	10-13	—	9.0	12	21	
32	Heated and Cooled Spts	HPT	1-2	4.8	10.0	—	26.8	
	Heated and Cooled Spts	LPT	3-8	—	9.0	4 to 12	13 to 21	
22A	Air Tube Case Heating	HPT	1-2	3.0	22.9	4	29.9	Manifolds 35%
22A	Air Tube Case Heating	HPC	10-13	9.9	20.3	4	34.2	Feed Tubes 24%
33	Cam Actuated Shroud	HPT	1-2	10.0	4.6	12	26.6	
33	Cam Actuated Shroud	LPT	3-8	13.0	13.0	10.0	36	
33	Cam Actuated Shroud	HPC	3-6	6-9	10.4	10.4	30.8	
33	Cam Actuated Shroud	HPC	10-13	10-4	10.4	10	30.8	
33	Movable Heat Shield	HPT	1-2	9.4	6.7	4.3	19.0	Torque tube 20%
	Movable Heat Shield	LPT	3-8	23.6	10.8	4.3	44.6	Pads 60%
38A	Heat/Cool Support Ring	HPT	1-2	19.6	2.8	15	37.4	
5	Rotor Shift	HPT	1-2	68.2	—	20	88.2	Gears 50%
	Rotor Shift	COMP	ALL	68.2		20	88.2	Length 20%

Weights do not include actuators, elec, plumbing, regulators

2.5.5 Life Cycle Cost Summary

The LCC estimates were generated for the 12 final schemes for both the fighter and transport applications using the model described in the previous section and inputs from appropriate other sections. The net ΔLCC estimates for these cases are shown in Tables 15 and 16 along with a breakdown of the respective costs and savings for each scheme. The results are grouped by mission and component and a ranking based on ΔLCC alone is given.

A review of these results contrasting the payoffs for fighter vs transport, different components, and different schemes is described. Emphasis is on identifying the key differences between groups and the main cause of these differences. The net LCC can conveniently be considered as having two parts: those items which increase the cost of the system "costs side" and those which decrease the cost of the system "savings side." In this study the acquisition, maintenance, and weight changes were "costs" on all schemes (net increase in LCC over the baseline), and the efficiency improvement due to improved clearances was the only "savings" item (net decrease in LCC over the baseline).

The "savings" and "costs" for each scheme, in LCC dollars, are given in Tables 15 and 16. These tables have three main columns: the "costs" (Column V), the "savings" (Column VI), and the "LCC change" (Column VII). The cost column (Column V) sums all the penalties resulting from incorporating a particular ACC scheme. It includes engine development costs (Column I), acquisition costs (Column II), maintenance costs (Column III), and weight costs (Column IV). The "savings" column lists LCC savings over the baseline for performance improvements which result from the tighter running clearances possible with ACC. The "LCC change" column gives the total LCC change from the baseline engine for incorporation of each ACC scheme.

Fighter vs Transport. Neither application shows a strong payoff for ACC throughout the engine, although both can benefit significantly from particular schemes applied to the high pressure turbine. The marginal to strongly negative payoff for ACC on all other components in both applications is due to different factors in each case.

On the "penalties" side (see previous paragraph for a description of benefits (savings) and penalties (costs)), the total LCC for a particular scheme is roughly the same for the fighter and transport applications although the weight contribution is much more important on the fighter than the transport (5:1 and approximately 40% of the total) while the maintenance contribution is more important in the transport than the fighter (5:1 and approximately 40% of the total). The acquisition and engine development costs are typically 40 to 50% of the LCC increase for all schemes.

On the "benefits" side the transport has no significant "benefits" except on the HPT. The fighter, however, has significant "benefits" in all components. This occurs even though the overall trade factor ΔLCC/Δclr is nearly twice as large for the transport as for the fighter. The difference is that little clearance is expected to be available for closedown on the transport at cruise on components other than the HPT. The Transport Clearance prediction represents the minimum clearance available with advanced future transports. The primary reason for the small available clearances is that the baseline assumed the best available bearing arrangements, rotor designs, and generally optimized the design for minimal clearance while operating the engine at an efficient high power during cruise. Current and near term future transports can have significantly larger clearances than the conservative values of this study, as discussed in Section 2.11. Considering these as representative of current engines and an upper limit on advanced transports, the net ΔLCC payoff for such transports were calculated assuming current and near term projected clearances. The net ΔLCC payoff for these clearances increases to the $100M range on the transport for some schemes. The clearance and payoffs available are then expected to fall between these limits and show a significant net payoff available for ACC on future transport aircraft.

TABLE 15. ACC LCC SUMMARY FIGHTER APPLICATION*

Line on Figure 108	Scheme	Stages	I Eng Devel +	II ACQ +	III Maint +	IV Wt =	V LCC Cost −	VI Perf Savings =	VII LCC Change
HPC Stages 6-9									
Axial Shroud Shift	6A	6-9	+25.9	+51.0	+4.4	+26.7	+108.0	−28.4	=+79.9
Strap Type Shroud	8	6-9	+ 8.7	+17.2	+2.7	+ 9.8	+ 38.4	−28.5	=+ 9.9
Pneumatic Seg Shroud	9	6-9	+ 4.7	+ 9.3	+3.2	+ 7.5	+ 24.7	−28.4	=− 3.7
Screw Thread Act. Shroud	10A	6-9	+30.2	+59.6	+4.5	+23.8	+118.1	−28.4	=+89.7
Bellows Act. Shroud	18	6-9	+11.1	+21.9	+5.8	+20.5	+ 59.3	−28.5	=+30.8
Cam Actuated Shroud	33	6-9	+20.3	+40.1	+4.1	+24.6	+ 81.1	−28.5	=+60.6
HPC Stages 10-13									
Axial Rotor Shift	5	ALL	+25.3	+49.8	+3.3	+70.4	+148.8	−65.0	=+83.8
Axial Shroud Shift	6A	10-13	+25.8	+50.8	+4.5	+34.0	+115.1	−36.4	=+78.7
Strap Type Shroud	8	10-13	+ 8.7	+17.2	+2.7	+10.6	+ 39.2	−36.4	=+ 2.8
Pneumatic Seg Shroud	9	10-11	+ 2.8	+ 5.5	+2.0	+ 5.0	+ 15.3	−20.6	=− 5.3
Screw Thread Act. Shroud	10A	10-13	+30.4	+60.0	+4.5	+23.9	+118.8	−36.4	=+82.4
Bellows Act. Shroud	18	10-13	+11.1	+21.9	+5.8	+20.5	+ 59.3	−36.4	=+22.9
Air Tube Case Cooling	31	10-13	+ 5.2	+10.2	+0.4	+16.0	+ 31.8	− 3.9	=+27.9
Heated and Cooled Supports	32	10-13	+11.4	+22.5	+3.5	+16.8	+ 54.2	− 3.9	=+50.3
Air Tube Case Heating	22A	10-13	+ 5.2	+10.2	+0.7	+21.5	+ 37.6	− 9.2	=+28.4
Cam Actuated Shroud	33	10-13	+20.4	+40.3	+4.1	+24.6	+ 89.4	−36.4	=+53.0
HPC Rear Seal									
Axial Shroud Shift	6A	Rear Seal	+11.4	+22.5	+2.3	+14.7	+ 50.9	Negligible	Concepts
Strap Type Shroud	8	Rear Seal	+ 6.0	+12.0	+1.7	+ 8.8	+ 28.5	Savings	Rejected
Bellows Act. Shroud	18	Rear Seal	+ 2.4	+ 4.8	+3.4	+14.4	+ 25.0		
HPT Stages 1-2									
Axial Rotor Shift	5	1-2	+25.3	+49.8	+3.3	+70.4	+148.8	−83.6	=+65.2
Air Tube Case Cooling	31	1-2	+ 2.9	+ 5.8	+1.0	+27.3	+ 37.0	−43.6	=− 6.6
Heated and Cooled Supports	32	1-2	+ 4.1	+ 8.2	+2.0	+21.4	+ 35.7	−72.8	=−37.0
Air Tube Case Heating	22A	1-2	+ 2.9	+ 5.8	+0.9	+23.8	+ 33.4	− 8.1	=+15.3
Cam Actuated Shroud	33	1-2	+10.8	+21.4	+4.0	+21.2	+ 57.4	−83.5	=−26.1
Movable Heatshield	35	1-2	+ 9.2	+18.2	+1.7	+15.2	+ 44.3	−32.0	=+12.3
Heated/Cooled Ring Support	38A	1-2	+ 9.1	+18.0	+3.4	+29.9	+ 60.4	−55.9	=+ 4.5
LPT Stages 1 and 2									
Heated and Cooled Supports	32	3-4	+ 4.0	+ 7.9	+2.6	+12.9	+ 27.4	−25.2	=+ 2.2
Strap Type Shroud	8	3-4	6.9	13.6	1.7	9.3	31.5	−25.2	=+ 6.3

*A description of each column is given in Section 2.5.4, and an explanation of how they are combined is given in Section 2.5.5.

TABLE 16. ACC LCC SUMMARY TRANSPORT APPLICATION

Line on Figure 108	*Scheme*	*Stages*	*I Eng Devel* +	*II ACQ* +	*III Maint* +	*IV Wt* =	*V LCC Costs* −	*VI Perf Savings*	=	*VII LCC Change*
HPC Stages 6-9										
Axial Shroud Shift	6A	6-9	+18.1	+50.0	+24.2	+ 4.8	+ 97.1	− 6.2	=	+ 90.9
Strap Type Shroud	8	6-9	+ 6.1	+16.8	+14.7	+ 1.8	+ 39.4	− 6.2	=	+ 33.2
Pneumatic Seg Shroud	9	6-9	+ 3.3	+ 9.1	+17.2	+ 1.3	+ 30.9	− 6.2	=	+ 24.8
Screw Thread Act. Shroud	10A	6-9	+21.1	+58.3	+24.4	+ 4.3	+108.1	− 6.2	=	+101.9
Bellows Act. Shroud	18	6-9	+ 7.8	+21.5	+31.3	+ 3.7	+ 64.3	− 6.2	=	+ 58.1
Cam Actuated Shroud	33	6-9	+14.2	+39.3	+21.9	+ 4.4	+ 79.8	− 6.2	=	+ 73.6
HPC Stages 10-13										
Axial Rotor Shift	5	ALL	+17.7	+48.7	+17.4	+12.6	+ 96.4	−10.4	=	+ 86.0
Axial Shroud Shift	6A	10-13	+18.0	+49.7	+24.3	+ 6.1	+ 98.1	− 4.2	=	+ 93.9
Strap Type Shroud	8	10-13	+ 6.1	+16.8	+14.7	+ 1.9	+ 39.5	− 4.2	=	+ 35.3
Pneumatic Seg Shroud	9	10-11	+ 1.9	+ 5.4	+10.7	+ 0.9	+ 18.9	− 2.4	=	+ 16.5
Screw Thread Act. Shroud	10A	10-13	+21.3	+58.7	+24.4	+ 4.3	+108.7	− 4.2	=	+104.5
Bellows Act. Shroud	18	10-13	+ 7.8	+21.5	+31.3	+ 3.6	+ 64.2	− 4.2	=	+ 60.0
Air Tube Case Cooling	31	10-13	+ 3.6	+10.0	+ 2.0	+ 2.9	+ 18.5	− 4.2	=	+ 14.3
Heated and Cooled Supports	32	10-13	+ 8.0	+22.1	+19.0	+ 3.0	+ 52.1	− 4.2	=	+ 47.9
Air Tube Case Heating	22A	10-13	+ 3.6	+ 9.8	+ 3.9	+ 3.9	+ 21.2	− 4.2	=	+ 17.0
Cam Actuated Shroud	33	10-13	+14.3	+39.4	+22.4	+ 4.4	+ 80.5	− 4.2	=	+ 76.3
HPC Rear Seal										
Axial Shroud Shift	6A	Rear Seal	+ 8.0	+22.0	+12.5	+ 2.6	+ 45.1			
Strap Type Shroud	8	Rear Seal	+ 4.2	+11.7	+ 9.1	+ 1.6	+ 26.6	Negligible Savings		Concepts Rejected
Bellows Act. Shroud	18	Rear Seal	+ 1.7	+ 4.7	+18.4	+ 2.6	+ 27.4			
HPT Stages 1-2										
Axial Rotor Shift	5	1-2	+17.7	+48.7	+17.4	+12.6	+ 96.4	−55.5	=	+ 40.9
Air Tube Case Cooling	31	1-2	+ 2.0	+ 5.6	+ 5.7	+ 4.9	+ 18.2	−55.5	=	− 37.3
Heated and Cooled Supports	32	1-2	+ 2.9	+ 8.0	+10.8	+ 3.8	+ 25.5	−55.6	=	− 30.1
Air Tube Case Heating	22A	1-2	+ 2.0	+ 5.6	+ 4.9	+ 4.3	+ 16.8	−55.6	=	− 38.0
Cam Actuated Shroud	33	1-2	+ 7.6	+20.9	+21.4	+ 3.8	+ 53.7	−55.6	=	− 1.9
Movable Heatshield	35	1-2	+ 6.5	+17.8	+ 9.4	+ 2.7	+ 36.4	−55.6	=	− 19.2
Heated Cooled Ring Support	38A	1-2	+ 6.4	+17.6	+18.1	+ 5.4	+ 47.5	−55.6	=	− 8.1
LPT Stages 3-7										
Strap Type Shroud	8	3-7	+ 6.8	+18.6	+17.4	+ 2.0	+ 44.8	−37.3	=	+ 7.5
Heated and Cooled Supports	32	3-7	+ 4.4	+12.0	+22.7	+ 5.5	+ 44.6	−37.3	=	+ 7.3
Air Tube Case Cooling	31	3-7	4.4	12.1	2.1	3.6	+ 29.8	−22.2	=	− 7.6

*A description of each column is given in Section 2.5.4, and an explanation of how they are combined is given in Section 2.5.5.

Component Comparison. The net payoff for ACC on different components generally follows the same trend for the fighter and transport applications. The per stage net LCC increase for a given scheme (i.e. penalties side) does not vary significantly for different components, although the cost for components requiring activation of more stages (HPC vs HPT) will be higher. The primary drivers for differences in payoff are the differences in clearances available for closedown and ΔLCC vs clearance influence coefficients. The influence coefficients are generally in the ratio of 2:4:1 for the HPC:HPT:LPT respectively, on both the transport and fighter. The clearances depend on mission and scheme. For the fighter the maximum available clearances are all in the 0.020 to 0.040 in. range, while for the transport they are generally in the ratio 1:4:8, HPC:HPT:LPT respectively. This is a result of the clearances available for closedown on the HPT and HPC being small (0.011 and 0.003 in. respectively) compared to the present day transport engine.

The HPT application is the most promising for both missions primarily because this component has the largest payoff per in. of clearance and a large available clearance to closedown. The transport has a larger number of effective clearance control schemes because of its higher inherent case thermal responsiveness and larger LCC to clearance trade.

Application to the HPC did not show a significant net ΔLCC benefit for any scheme in either the fighter or transport. The lack of payoff is due to significantly reduced trade factors (compared to the HPT) in the fighter, and the combination of smaller trade factors and small available clearances on the transport. Current and near term advanced transport engines show similar trends, where significantly less clearance is available for closedown in the compressor than the turbine. Using the current and near term advanced engine clearances as an upper bound on the clearances available there would be a net ΔLCC savings for some clearance control schemes on the transport compressor. The net payoff would increase if the controls could be combined with the controls of similar ACC schemes elsewhere in the engine to eliminate unnecessary duplication.

The low pressure turbine shows a small payoff for some schemes in both the fighter and transport applications. The lack of a significant payoff was due to the small trade factor (typically 1/4 of HPT value) for this component. It was only because the clearance closedowns were so large that any benefit was achieved.

Application of ACC to the LPC and compressor discharge seal was considered on preliminary review. It was found unattractive because of the combined larger costs and significantly smaller payoffs of these applications as compared to the other components considered.

2.5.6 Scheme Comparison

A comparison of the net ΔLCC for different schemes shows that for a given component, schemes of a similar type (mechanical, pneumatic, or thermal) generally performed the same. There are important exceptions to this, however, particularly for schemes that were not capable of closing down clearances over the full range available. The schemes that paid off did so generally because they were lighter and simpler, yet just as effective as the less desirable schemes. The principal differences were on the penalty rather than the benefits side. The only schemes that were benefits limited were the low pressure cooling schemes on the fighter.

2.6 WEIGHT SUMMARY

The weights for the 12 final ACC schemes are summarized in Table 14. The results are first broken down by component, then the case, linkage, and control contributions are itemized for each component.

The method of calculating weights utilized similarities in the size, materials, and geometry of stages within each component. Within any one component, the stage-to-stage variations in size, weight, and geometry were small. This permitted calculating detailed weights for representative stages, then scaling the weights for the adjacent similar stages. The stages analyzed in detail were HPC stages 6 and 11, HPT stage 1, and LPT stage 3.

The detailed weights were calculated from the design sketches shown in Figures 66 through 101. In addition to the weights summary, the key contributors to the increase in weight for each of the ACC schemes have been identified in Table 14. The weight of materials replaced by the ACC schemes was in all cases subtracted from the weight penalty charged against each ACC scheme. A review of the weights given in Table 14 shows a large scheme-to-scheme variation with a net increase for all schemes.

The heaviest scheme is the rotor shift scheme at $\Delta wt = +88$ lb. For the high pressure turbine, the remaining schemes all fall between 19 and 37 lb. No single factor (case, linkage, or controls) is the predominant contributor. The control weight is typically being 20 to 40% of the total, while case modifications account for 10 to 50%, and the linkage from 7 to 70%. No one type of scheme (thermal or mechanical) is predominantly heavier or lighter than the other.

The compressor and LPT do have some applicable schemes with significantly lower weights. These schemes are the pneumatic shroud (scheme No. 9 at 9.4 lb), and the cinch shroud (scheme No. 8 at 13.3 lb).

2.7 RELIABILITY

A summary of the reliability estimates on the 12 final schemes is shown in Table 12 where the reliability penalty above the baseline is given for each scheme. The reliability estimates were based on the mean time between failure (MTBF) for every piece of new hardware required for each scheme. The MTBF is inversely proportional to the reliability index $\Delta\lambda$ (failure per 1000 flight hours). The estimates were generated by considering the historical failure modes of each part and then assessing for new modes. Base failure rates for parts analogous to F100 parts and having similar failure modes were determined from data. These failure rates were adjusted for mechanical complexity and for number of applications. In cases where no failure rate data was available, engineering judgment and historical data were used to form reliability estimates. Analysis indicates that in those schemes requiring either valving or diameter changes induced by thermals, the largest reliability drivers were the valving systems and the case cracking by thermal stress. This conclusion is borne out by ACC experience on P&WA commercial engines.

The controls reliability contributed significantly to the overall reliability detriment for all schemes, generally half or more of the total.

The failure rates for the HPT shown in Table 12 range over a $0.13 < \Delta\lambda < 0.40$, omitting the rotor shift scheme. This scheme is the least reliable and is not characteristic of the other mechanical schemes. In general, the thermal schemes are significantly more reliable than the remaining mechanical schemes ($13 < \Delta\lambda_{THERMAL} < 22$) versus $23 < \Delta\lambda_{MECHANICAL} < 35$). This degree of reliability does not eliminate the mechanical schemes from consideration.

2.8 MAINTAINABILITY

A summary of the maintainability requirements of the 12 ACC schemes is shown in Table 13.

The maintainability assessment was based on time required to remove and reinstall the required item. Because it was usually an insignificant part of total maintainability, time required to repair subassemblies once they were removed from the engine was not a direct factor. Disassembly was assumed to start from a complete engine, and included the time required to remove the engine and the surrounding modules from the affected area. It was further assumed that if one part was repeated on several stages of a component, all of the similar parts would be replaced upon disassembly for failure of any one of the parts. This was not a driving assumption since the majority of the maintainability cost was incurred in engine subassembly removal to expose the failed part.

This approach is conservative because frequently parts identified as having failed no longer met some tolerance criteria due to wear and did not fail catastrophically causing the system to malfunction. Replacement of such "failed" parts often occurs upon routine engine teardown for maintenance or for teardown due to catastrophic failure of some other part. Costs generated for "failures" of such parts should not require that the full cost of engine teardown and rebuilding be credited against the failed part in question.

A detailed evaluation of which parts would fail and in what modes and the degree to which the teardown costs should be credited against each scheme is beyond the scope of this work. The conservative approach of assuming that an entire teardown is credited against each failure was adopted.

2.9 COST

An itemized breakdown of the original equipment cost for the 12 schemes is listed in Table 17. This breakdown gives case, linkage, and control costs for each component application of each of the 12 schemes.

In developing these estimates representative stages from each component were selected for detailed analysis. Costs of adjacent similar stages were scaled from these detailed estimates by considering the size, material, and geometry differences. The stages analyzed in detail were HPC stages 6 and 11, HPT stage 1, and LPT stage 3. The costs were developed from Figures 66 through 101 for the representative stages. In some of the schemes one part served several stages such as a lever arm, torque tube, or air bleed manifold and tube. The cost of such items was computed then equally distributed over the affected stages. In all situations the cost of assemblies that were replaced by ACC assemblies were subtracted from the cost of the ACC assembly. Generally these costs were not significant.

A review of the results shows a significant variation in the costs of the various schemes, with the cost per stage without controls ranging from $960 to $5801 for the HPT. This is without considering the $39,500 cost of the axial rotor shift scheme which was more than twice as expensive as the next nearest scheme. Differences in controls costs were significant and tended to further increase the spread. For the two stages of the HPT the least expensive scheme costs $3500 per engine, while the most expensive costs nearly $13,000. These differences are significant to the overall LCC of the system. Thermal schemes were generally much less expensive than the mechanical schemes since little or no modifications were required of the core structure. An exception to this is the thermal fast response ring that required substantial core reworking and consequently cost nearly as much as the mechanical schemes.

TABLE 17. COST DATA (SUMMARY)

Scheme	Description	Location	Case $	Linkage $	Sub Total	Controls $	Total $
5,37	Axial Rotor Shift	HPT 1&2	7,059	12,430	19,489	11,000	30,489
		HPC 10-13	7,059	12,430	19,489	11,000	30,489
30	Shift	HPC 10-13	9,776	14,904	24,680	6,000	30,680
		HPC 6-9	9,929	14,904	24,833	6,000	30,833
8	Shroud	HPC 10-13	4,388	1,770	6,108	6,000	12,108
29		HPC 6-9	4,388	1,770	6,108	6,000	12,108
		LPT 3-8	6,120	2,095	8,215	N/A	14,215
9	Shroud	HPC 10-11	2,314	N/A	2,314	1,000	3,314
		HPC 6-9	4,628	N/A	4,628	1,000	5,628
		LPT 3-8	8,670	N/A	8,670	1,000	9,670
10A	Actuated Shroud	HPC 10-13	15,068	14,904	29,977	6,000	35,972
		HPC 6-9	5,068	14,904	29,972	6,000	35,972
17	Shroud	HPC 10-13	11,248	N/A	11,248	2,000	13,248
28		HPC 6-9	11,248	N/A	11,248	2,000	13,248
20	Air Tube Case Cooling	HPT 1&2	N/A	2,676	2,676	800	3,476
20		HPC 10-13	N/A	5,352	5,352	800	6,152
21	Heated & Cooled Supports	HPT 1&2	N/A	1,920	1,920	3,000	4,920
32		HPC 10-13	N/A	10,616	10,616	3,000	13,616
39		HPC 6-9	N/A	10,616	10,616	3,000	13,616
		LPT 3-8	N/A	5	4,405	3,000	7,405
22	Air Tube Case	HPT 1&2	N/A	2,676	2,676	800	3,476
		HPC 10-13	N/A	5,352	5,352	800	6,152
33	Cam Actuated Shroud	HPT 1&2	5,280	1,616	6,896	6,000	12,896
		HPC 10-13	15,000	3,328	18,316	6,000	24,316
		HPC 6-9	15,000	3,328	18,316	6,000	24,316
35	Movable	HPT 1&2	9,902	N/A	N/A	1,100	11,002
38	Heated/Cooled	HPT 1&2	5,880	0	5,880	5,000	10,880

TABLE 17. COST DATA (SIGNIFICANT DRIVERS) (Continued)

Number	Description	Comments
5	Axial Rotor Shift, Compressor, Turbine	Outside drive linkage is 35% of cost
6A	Axial Shroud Shift, 4-8 Compressor	"T" section ring under shroud is 45% of cost
	Axial Shroud Shift, LPT	Shroud and Case is 50% of cost
	Axial Shroud Shift, Rear Compressor Seal	Seal ring assy is 45% of cost
10A	Screw-Act. Shroud, LPT, 3-4	Case is 30% and shroud seg 33% of cost
	Screw-Act. Shroud, Compressor 6-11	Case is 30% and shroud seg 29% of cost
	Screw-Act. Shroud, Compressor 12-13	Case is 32% and shroud seg 27% of cost
18	Bellows-Act. Shroud, Compressor 4-13	Case is 33% and bellows 37% of cost
31	Air Tube Heat/Cool, Compressor 9-13	Footed vs strip vane is 73% of cost
22A	Air Tube Heat/Cool, HPT 1-2	From JT9D estimated valving is 55% of cost
33	Cam-Act. Shroud, HPT 1-2	Vane configuration change is 60% of cost
	Cam-Act. Shroud, Compressor 4-5	Actuator ring is 55% of cost
	Cam-Act. Shroud, Compressor 6-13	Actuator ring is 55% of cost
35	Movable Heatshield, HPT 1-2	Heatshield assy's are 32% of cost
38A	Heat/Cool Ring Support, HPT 1-2	Changed vane feet is 28% and support ring 26% of cost

Design of the thermal schemes generally assumes little or no case modifications. Additional modifications may, however, be required to eliminate the stresses that arise when the cooled outer case attempts to compress the still-warm inner case adjacent to the gas path. The effectiveness of case thermal schemes and the cost of internal modifications required to achieve additional clearance changes would have to be carefully determined on an application-by-application basis.

2.10 SCHEDULING

The level of control required for each leg of each mission was evaluated to determine the benefits of higher levels of control. The type of controls and schemes applicable to a given leg of either mission depend on both the number of different clearance levels required in that leg and the rate at which clearance changes must be accomplished to avoid rubs.

The missions were divided into legs based on the minimum level of control (on/off, open loop, or feedback) required to accomplish the available clearance benefit for each leg. The missions shown in Figures 64 and 65 were divided into steady-state cruise, steady-state climb, and transient legs. On/off controls were assumed to be applicable only to the cruise legs, open loop controls to both cruise and SS climb, and feedback controls to the entire mission. Based on the transient thermal analysis it was further determined that the engine requires approximately one minute to reach steady-state clearances after an acceleration and five minutes after a deceleration transient. The time to reach equilibrium was subtracted from the steady-state and climb portions of the missions when determining the time over which the ACC could be applied. Table 18 lists the breakdown by time and fuel usage for both the fighter and transport missions over the steady-state cruise portion, steady-state cruise and climb portions, and the entire mission.

A review of this table shows that for the transport mission, 89% of the fuel and 93% of the time is spent at SS cruise where simple on/off controls are sufficient. Open loop feedback allows operation during only an additional 5% of the fuel burned (99-89%), and full real time clearance measurement and feedback allows savings during only an additional 11% (100-89%) of the fuel burned over the on/off mode of operation. Nearly 90% of the total benefit of ACC can be accomplished with a simple on/off system.

For the fighter mission, Table 18 shows that on/off control is feasible during 69% of the fuel burning and 75% of the total mission time. While this figure is substantially less than for the transport, the majority (nearly 70%) of the mission based on fuel consumption is spent where on/off controls are applicable. Only an additional 7% of the fuel time is spent at SS climb, while fully 31% is spent during climb or transient operation. Significantly larger portions of the fuel time are available for fully modulated feedback control in the fighter mission compared to the transport mission, but there is little opportunity for open loop control in either mission when the clearance available does not vary over the cruise and dash portions of the mission.

2.10.1 Influence Coefficients

Reductions in the baseline clearance for each ACC concept were translated into LCC changes through the use of influence coefficients. These influence coefficients were generated using conceptual meanline designs of the affected components and expected mission and fleet usage profiles of the engines and aircraft.

The algorithm used to relate LCC to clearance is shown in Table 19. This equation contains two terms. The first relates clearance improvements to ΔLCC improvements through component efficiency and thrust specific fuel consumption (TSFC) improvements. The second also relates clearance improvements to ΔLCC improvements, but accounts for engine size changes required to

resize thrust back to the original required level after component efficiency changes have altered the engine thrust. Values for each of the trade factors in this equation, for both the fighter and transport applications, are given in Table 20. These factors were generated for representative advanced fighter and transport engines.

The ΔLCC effect of incorporating ACC schemes used to evaluate the given concepts would not have changed significantly if the study had been performed on other advanced cycles because it is the difference from a baseline and not the absolute level of LCC that is of interest. Another baseline cycle may have an overall baseline fleet LCC which is different from the baseline of this study, but the benefits of a given ACC scheme evaluated from either baseline would not be significantly different.

TABLE 18. CONTROL ADVANTAGES*

Advantages for different levels of control, as measured by the fraction of mission over which advantages can be gained.

Mission	*Mission Time With ACC Active* (min)	(%)	*Portion of Fuel Burned During Which ACC Is On* (lb)	%
Fighter Mission				
Total Mission	155		18,000	
On/Off (SS Cruise)	88	57	12,500	69
Open Loop (SS Cruise and SS Climb)	117.5	76	13,600	76
Feedback (Entire Mission)	155	100	18,000	100
Transport Mission				
Total Mission	700		153,600	
On/Off (SS Cruise)	648	93	136,200	89
On/Off (SS Cruise and SS Climb)	684	98	144,200	94
Feedback (Entire Mission)	720	100	153,600	100

*Refer to Sections 2.2.3 and 2.10 for discussions of this table.

TABLE 19. ΔLCC VS ΔCLR ALGORITHM

$$\Delta LCC = \frac{\Delta\eta}{\Delta CLR}\;\frac{\Delta CLR}{0.010''}\left\{\underbrace{\frac{\Delta LCC}{\Delta TSFC}\;\frac{\Delta TSFC}{\Delta\eta}}_{\text{Term 1}} + \underbrace{\left[\left(\frac{1}{\frac{F_n@\Delta\eta}{F_{nbase}}}\right)^x - 1\right]\frac{\Delta LCC \times 100\%}{\Delta\%wt}}_{\text{Term 2}}\right\}$$

$$\Delta LCC_{TOTAL} = \Delta LCC_{HPC} + \Delta LCC_{HPT} + \Delta LCC_{LPT}$$

where

* $\frac{\Delta\eta}{\Delta CLR}$ = change in component efficiency for 0.010 in. clearance change

* $\frac{\Delta TSFC}{\Delta\eta}$ = change in mission cruise/dash avg TSFC for 1% $\Delta\eta$

* $\frac{\Delta LCC}{\Delta TSFC}$ = change in life cycle cost for 1% ΔTSFC

* $\frac{\Delta CLR}{0.010 \text{ in.}}$ = change in effected clearance per 0.010 in.
  (for ΔCLR = 0.030 in. => $\frac{\Delta CLR}{0.010} = 3$)

* ΔLCC = change in fleet life cycle cost (millions of $)

$\frac{F_n@\Delta\eta}{F_{nbase}}$ = change in thrust due to change in component efficiency

$\left(\frac{1}{\frac{F_n@\Delta\eta}{F_{nbase}}}\right)^x - 1$ = change in engine weight required to resize thrust back to original level after efficiency change

x = exponent in thrust vs weight trade (assumed = 1 for this study)

$\frac{\Delta LCC}{\Delta\%wt}$ = change in fleet life cycle cost for a percent change in engine weight

TABLE 20. INFLUENCE COEFFICIENTS

	Coefficient	HPT Stages 1 and 2	HPC 10-13	HPC 10-11	HPC 6-9	LPT* 3-4	LPT** 3-8
Δ% Component Eff per 10 Mils Δ Clearance	Δη/10 mils ΔCLR	0.86	0.44	0.25	0.43	0.29	0.25

	Coefficient	Fighter HPT	Fighter HPC	Fighter LPT	Transport HPT	Transport HPC	Transport LPT
Δ% TSFC vs % Component Eff	ΔTSFC/Δη	-0.60	-0.55	-0.42	-0.80	-0.70	-0.81
Δ% Thrust/Δ% Component Eff	ΔFn at Δη/Fn Base	0.998	0.998	0.999	1.0074	1.0123	1.0078

	Coefficient	Fighter (mil)	Transport (mil)
ΔLCC/Δ% TFSC	ΔLCC/TSFC	66	67
ΔLCC/Δ% Engine Wt	ΔLCC/% Wt	29	7

ΔLCC (Mill $)/0.01 in CLR	HPC 6-9	HPC 10-13	HPT 1 and 2	LPT
Transport	-21.0	-20.6	-50.5	-14.9
Fighter	-13.3	-13.6	-29.1	- 7.2

*Fighter

**Transport

Influence Coefficient Ground Rules. The influence coefficients were calculated using the assumed mission and fleet makeup profiles and additional assumptions concerning scheme operation and performance of the engine. The significant assumptions for each trade factor are detailed below.

Component efficiency vs clearance ($\Delta\eta/\Delta CLR$) trades were generated for each stage of each component. Based on the mission review conclusions that 70 to 90% of the fuel was used at the SS points (40k/0.9, 10k/1.2, 35k/0.8), the performance trades were generated at these points. All three cycle points are at essentially the same component operating condition, so a single trade factor for each component or group of stages represented the mission average influence coefficient of that component for both applications. (See Table 20.)

The trade factors were given as the average efficiency improvement over the entire component even though the clearance of the entire component was not affected by the particular scheme. This was required in order to make the efficiency-to-clearance trade factor compatible with the TSFC/efficiency trade factor which applies to entire components only. The efficiency vs clearance trade also varies depending on whether just the blade tip clearance or the blade tip plus stator tip clearance changes. Any particular control scheme will operate in one or the other of these modes.

The TSFC vs component efficiency and engine thrust vs efficiency influence coefficients were mission average values based on the dash or cruise mission legs. These coefficients were generated for each component for each of the two missions and accounted for cycle differences between the low bypass ratio mixed flow design of the fighter and high bypass ratio nonmixed flow for the transport. The influence coefficients were generated for the two different efficiency levels assuming constant match, constant V_{jd}/V_{je}, and constant CET. This approach is consistent with the assumed new engine/new aircraft application where the engine areas (engine size) are varied with efficiency changes, rather than assuming a constant operation line as would be appropriate for a fixed geometry mature engine.

The engine thrust trade factor was applied for both missions even though the required thrust level in the fighter mission was sized for the combat point where ACC was assumed not to be operating. This was done to account for efficiency changes at the cruise point affecting the thrust required at combat. For the new aircraft application, improvements in cruise TSFC will allow a lighter aircraft, hence less thrust will be required at combat settings.

The LCC vs TSFC or engine weight trades were generated for the specific aircraft, mission, and fleet assumed for each application. The particular models used were developed previously at P&WA specifically for the ATF and C141X applications. The mission average LCC influence coefficients were generated assuming the TSFC improvements were in effect only on the dash and/or cruise legs of the respective missions.

The overall influence coefficients (fleet ΔLCC vs ΔCLR) listed in Table 19 were generated from the above factors using the equation in Table 20. A review of these results shows the transport trade factors to be 50 to 75% higher than the fighter factors. Clearance improvements in the HPT are seen to be about two times more effective than changes in the high pressure compressor and about four times more effective than changes in the LPT for both missions.

2.10.2 Alternate Trade Factors

The conclusions of this study were based on the LCC benefits of ACC for a fixed mission. Alternate approaches to utilizing ACC efficiency gains in terms of improved mission characteristics at a fixed LCC may, however, be of interest. Alternate trades of interest are listed in Table 21.

TABLE 21. ALTERNATE TRADES OF INTEREST

Factor	*Fighter*	*Transport*
TOGW/1% Engine wt	140 lb/%	450 lb/%
TOGW/1 lb Engine wt	3.3 lb/lb	9.3 lb/lb
TOGW/1% TSFC	450 lb/%	2700 lb/%
Specific Range/lb Fuel	0.13 nm/lb Fuel	0.036 nm/lb Fuel

2.10.3 Thermal Analysis

The thermal analysis conducted in support of the structural clearance calculations utilized existing thermal models of the engine case and rotor. These models were modified to reflect the altered mission and performance levels of the baseline fighter and transport applications, as well as specific modifications to model the functioning of thermal type ACC schemes.

The thermal analysis is performed using a computer solution to a modal breakup of the structure where the appropriate conduction, convection or radiation boundary conditions have been specified on each node. The general analytical approach and the particular model used in this study have been experimentally verified over a wide range of operating and environmental conditions, including both steady-state and transient operation.

The analysis was divided into baseline and modified environment sections. The baseline analysis, performed for both the fighter and transport missions, calculated the thermal response during transients and the temperature level at each state of the baseline structure with no ACC modifications. Engine inlet conditions and detailed stage-to-stage variations in thermal environ-

ment were modeled as was appropriate to each mission and the assumed engine performance level. This baseline was assumed to represent the thermal environment of both a structure without any ACC and a structure where mechanical ACC schemes were installed. The thermal environment for the mechanical schemes was assumed to be the baseline environment. This was justified in that the baseline environment was not materially altered by the mechanical schemes, and any thermal level change effects could be factored out mechanically.

There were several significant differences between the transport and fighter baseline thermal environments. These differences result from the fighter being a ducted mixed flow turbofan where the bypass air washes the outside of the compressor and turbine cases, while the transport engine separated the core and bypass air by an intermediate wall. The case thermal environment on the fighter engine is controlled by the relatively strong convective heat transfer generated by the pressurized hot fan duct air. By comparison, the transport core engine cases see a relatively stagnant chamber with low heat transfer to a very nearly ambient chamber.

This difference in case environment results in the transport cases running warmer and having a slower response than the fighter cases. As a result, there is a more severe acceleration pinch due to the slower response, and a relatively larger steady-state operating clearance at cruise because of the warmer cases.

For the same supply air conditions thermal ACC schemes are potentially more effective on transport applications because of the lower baseline cooling effectiveness.

2.10.4 Parasitic Losses

Adapting ACC schemes to the base engines induces parasitic losses in the system that reduce the overall benefits of the ACC. These losses can be considered as either direct losses required to power or activate the scheme, or indirect losses such as flow blockages or induced leakages that are a direct result of the scheme but are incidental to its operation.

Thermal Schemes. Operation of both the low-pressure case cooling/heating, and high-pressure fast response and heated and cooled supports schemes required significant amounts of bleed air when operating. In order for there to be a significant penalty for any particular scheme, the bleed air had to be taken over a long portion of the mission (cruise/dash), and had to be dumped without further use. The indirect losses for thermal schemes were the increased duct resistance due to the presence of plumbing and controls in the duct. For the geometries considered, experience has shown these to be negligible.

The case heating scheme was only activated during transients, which was both a short portion of the mission and one where the effects of bleeding LPT air did not affect performance. No direct performance penalty was computed for this scheme.

The case cooling scheme did require significant cooling air (0.8% WAE) during the entire cruise leg. After use, the cooling air was dumped into the fan duct (fighter) or overboard (transport) as appropriate. A performance penalty was therefore calculated in order to account for the loss in the work performed on this air over the cruise/dash legs. The performance penalty was taken between the supply and dump states.

The high pressure fast response and the heated and cooled support schemes were activated during cruise, but secondary use could be made of the air after ACC. For both types of schemes the cooling requirements to the turbine case allowed turbine schemes to substitute spent ACC air for other required cooling air. No direct penalty was identified for these schemes in the turbine. There was, however, a direct penalty for the compressor since the air was dumped into the fan duct. A performance penalty was carried for the compressor application.

The pneumatic and mechanical schemes had both direct and indirect losses. The indirect losses due to structural duct flow blockage was considered small based on experience and was neglected as in the thermal schemes. These schemes induce additional blockage and leakage in the main gas path not found in the thermal schemes. It results from the outer air seals moving independently of the cases causing small steps between the OAS and the case. Experience shows penalties associated with these features are small, particularly if care is taken in design to minimize the effects. Such design considerations would include minimizing the total area of slots and gaps, sealing the movable OAS against air backflowing under the seal, and designing the seal face to be conical, hence always giving rearward facing steps. No system penalties were calculated for indirect losses on the pneumatic or mechanical schemes because the required power was small.

System power drains for the pneumatic and mechanical schemes (with the exception of the movable shroud scheme) only occurred when the systems were being activated. During the entire time of operation only a static load was required in order to overcome the aerodynamic restoring forces. This was accomplished without extracting any work from existing systems and consequently induced no system penalty. No operating losses were then calculated for either the mechanical or pneumatic schemes. The pneumatic shroud scheme required a constant flow of compressor discharge air to overcome leakage around the seals. A penalty for this leakage was considered.

2.11 CLEARANCE ANALYSIS

2.11.1 Scope

A clearance analysis was performed on the baseline geometry of both the transport and fighter applications for the actual missions and cycles of this study. The achievable clearance for each scheme type was then evaluated accounting for the effects of ACC hardware.

2.11.2 Fighter Clearance Analysis

Baseline Clearances. The advanced tactical fighter mission is represented in Figure 109. This mission was divided into six transients requiring analysis (circled areas of Figure 109). These six transients are described as follows:

1. Take off at sea level
2. Deceleration to cruise at 35k/0.9 Mn
3. Descent from 35k/0.9 Mn
4. Acceleration to supersonic dash at 10k/0.9-1.2 Mn
5. Combat at 10k feet
6. End dash at 10k/1.2 Mn and climb to 45k/0.9 Mn and decelerate to cruise at 45k/0.9 Mn.

Analysis of Baseline Transients. A detailed thermal and structural analysis of the baseline transients was performed to determine the mission point at which the most severe pinch or closedown occurred at each stage of the high compressor and high turbine. The worse transient was consistently found to be transient No. 5 (combat at 10,000 feet). The HPT first blade tip clearance baseline results are shown in Figure 110 illustrating the fighter clearance trends.

Analysis of Thermal ACC Schemes. The addition of thermal ACC hardware to the baseline engine changes the thermal and structural response of the cases. The response of the system with ACC hardware was then reexamined during the worst transient (combat) to determine if the available clearances had changed with the addition of the ACC hardware.

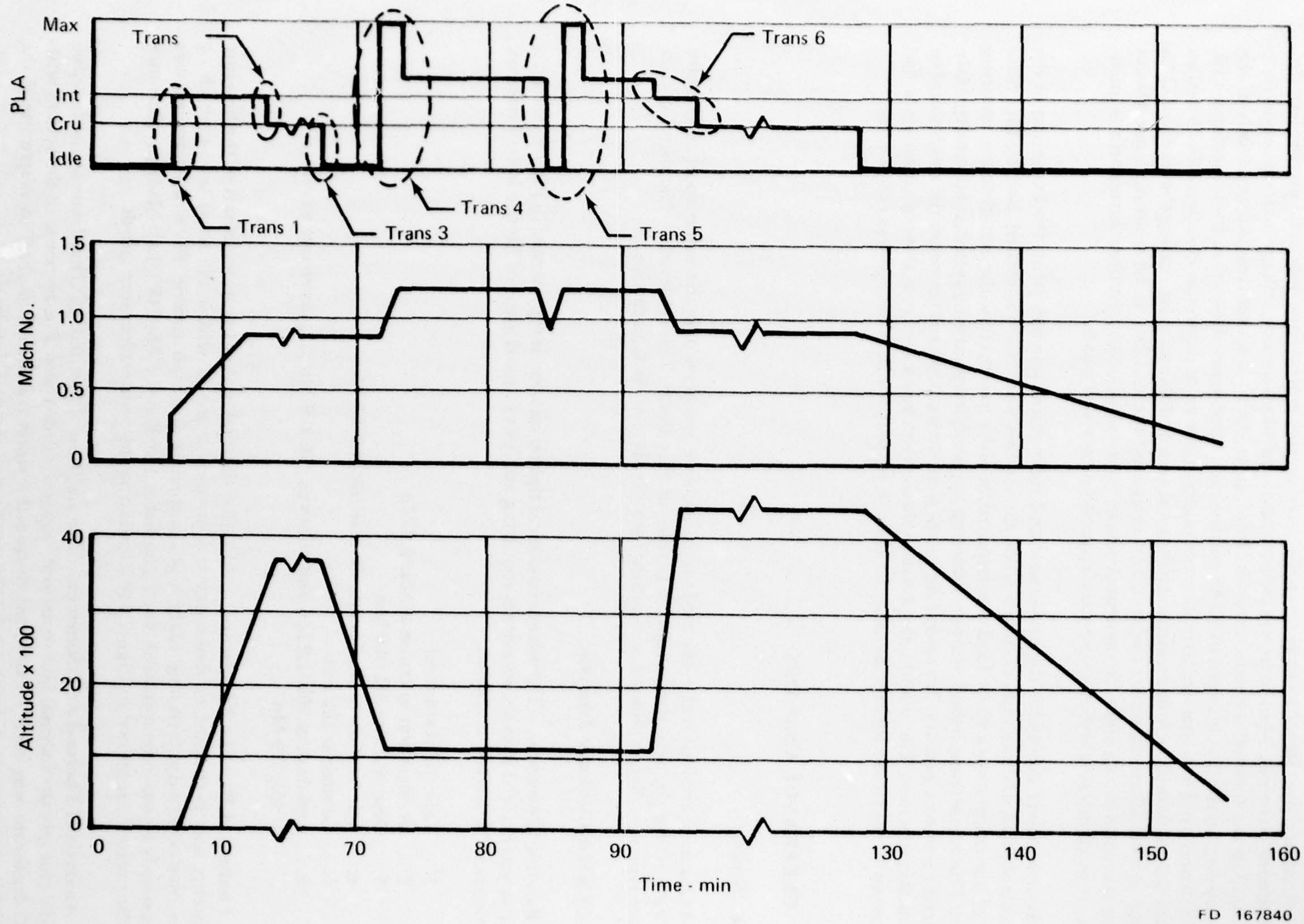

Figure 109. Fighter Mission

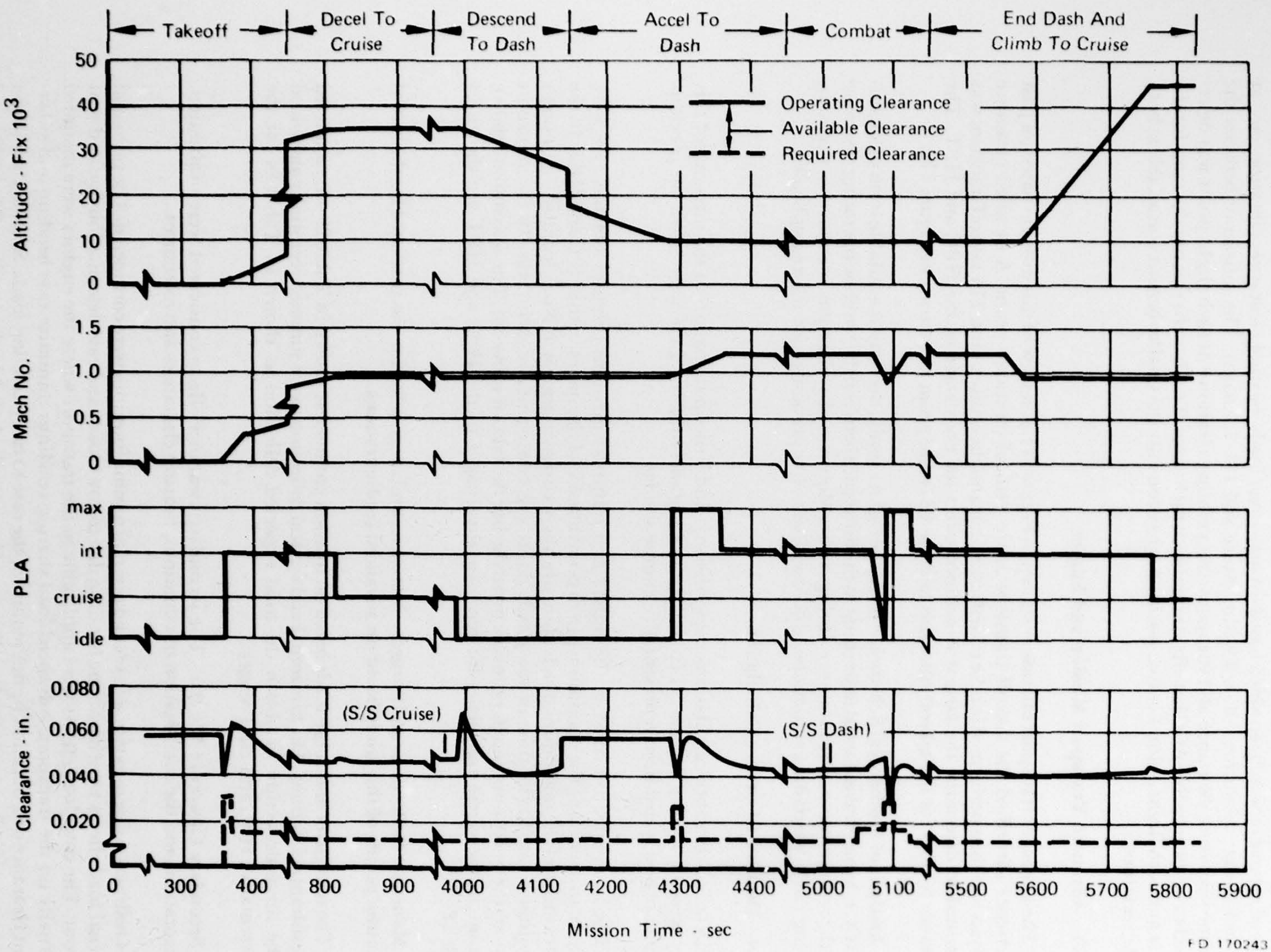

Figure 110. Fighter HPT 1st Blade Tip Baseline Clearance History

Analysis of Mechanical Schemes. The clearance benefit available with mechanical ACC schemes was calculated assuming that these schemes were inactive during transients. The minimum required clearance was determined based on maneuver loads, bearing clearance, vibration, etc., at two steady-state conditions (35k/0.9 Mn, cruise and 10k/1.2 dash). The difference between the baseline operating clearance and the required operating clearance at each flight point was determined to be the possible ACC benefit attainable at each stage. This benefit was not the same for the cruise and dash flight point. For two-position actuation only the smaller benefit is available at both flight conditions.

2.11.3 Advanced Transport Mission and Engine

The advanced transport mission is shown in Figure 111. A review of this mission based on past experience identified the takeoff transient as the critical clearance point. A detailed clearance analysis was then performed for the takeoff transient and the cruise point. The takeoff transient was examined to determine the largest closedown effect for each stage of the HPC and HPT. The clearance history for the takeoff transient and the SS cruise point are shown in Figure 112.

Analysis of Mechanical Schemes. As in the fighter study, the benefit available from mechanical ACC schemes was assumed to be equal to the difference between the baseline operating clearance and the required operating clearance during cruise. Mount load ovalization, maneuver deflections, bearing radial clearances, vibrations, and cowl loads were accounted for where applicable.

2.11.4 Detailed Clearance Calculations

Detailed clearance calculations using thermal and structural analysis of the missions of this study were performed for the HPC and HPT. Clearances for the LPT were based on previous experience and scaled from representative engine studies.

The transients identified in the fighter and transport missions (Figures 109 and 110) were analyzed to determine the maximum pinch point at each of the stages in the HPC and HPT. In the fighter mission the maximum pinch point always occurred in transient No. 5 (combat). Although magnitudes varied, the time of the pinch point was consistent for each stage. In the transport mission, the maximum pinch point occurred during the takeoff transient. The maximum relative motions in the worse transients for representative stages in the HPC and HPT are shown in Table 22.

Maneuver Deflections and Surges. Maneuver and surge behavior was predicted for the initial operating points of this study based on advanced configurations.

The maneuver and surge loads based on mission parameters shown in Table 23 were analyzed for resultant deflections. The horizontal and vertical deflections were summed vectorially and added to the surge deflection to obtain the total expected deflection as shown in Table 24 for the representative HPC and HPT stages.

Secondary Clearance Effects. The secondary clearance effects considered were ovalization, deterioration, and the combination of vibrations, bearing clearances and tolerances.

Ovalization due to external loads and thermal nonuniformities were considered. The principal external load effects were backbone bending due to cowl loads and case deformation due to thrust takeout. The cowl load effects were applicable to the transport where the engines were mounted externally on the transport. Advanced load sharing cowlings minimize case bending and subsequent clearance deterioration by not requiring the case to carry bending loads. Symmetrical thrust takeout to minimize thrust load ovalization effects was included in the baseline. This advanced structural technique significantly reduces clearance deterioration due to ovalization and is expected to be incorporated in advanced engine mounting systems.

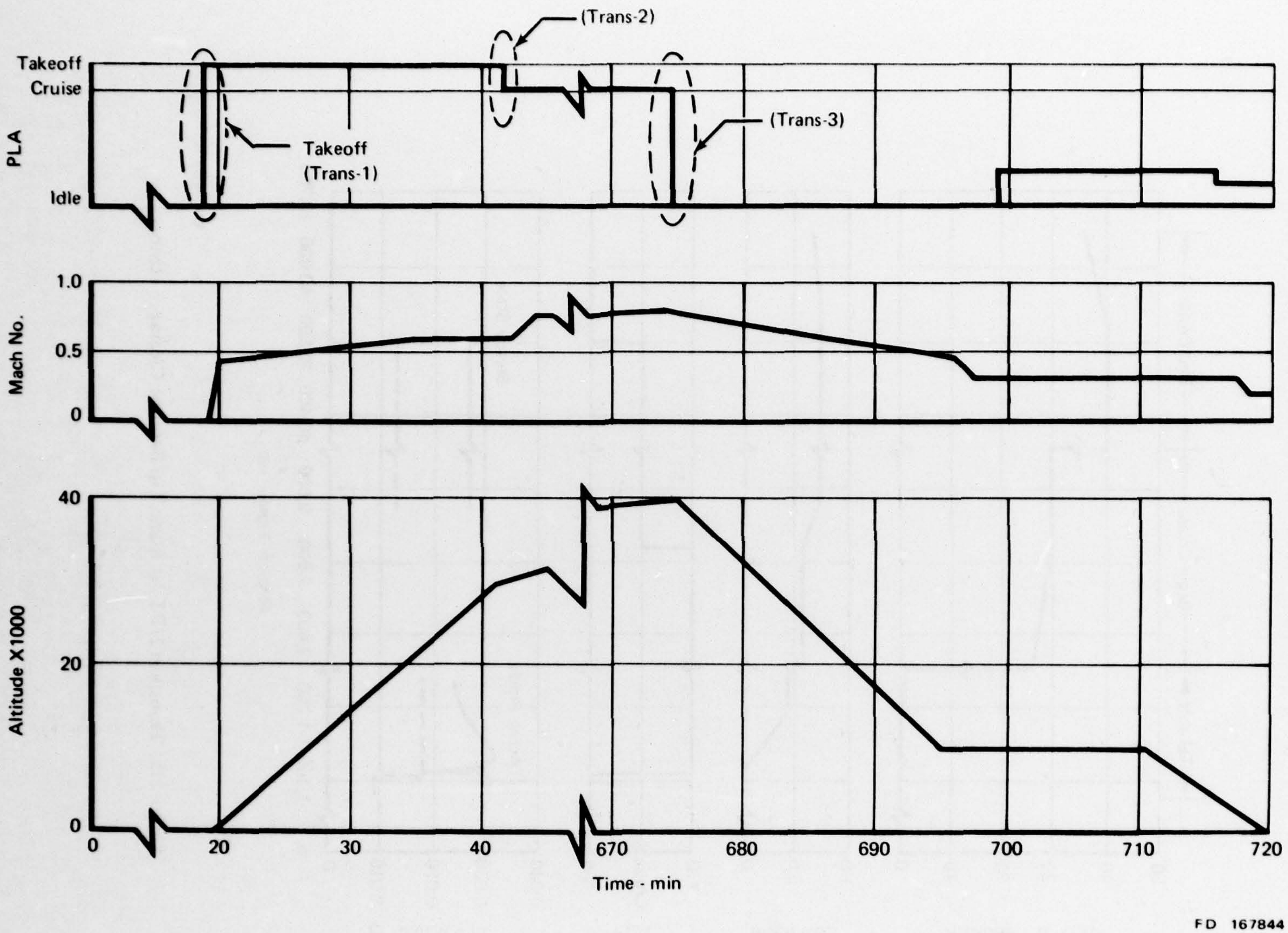

Figure 111. Transport Mission

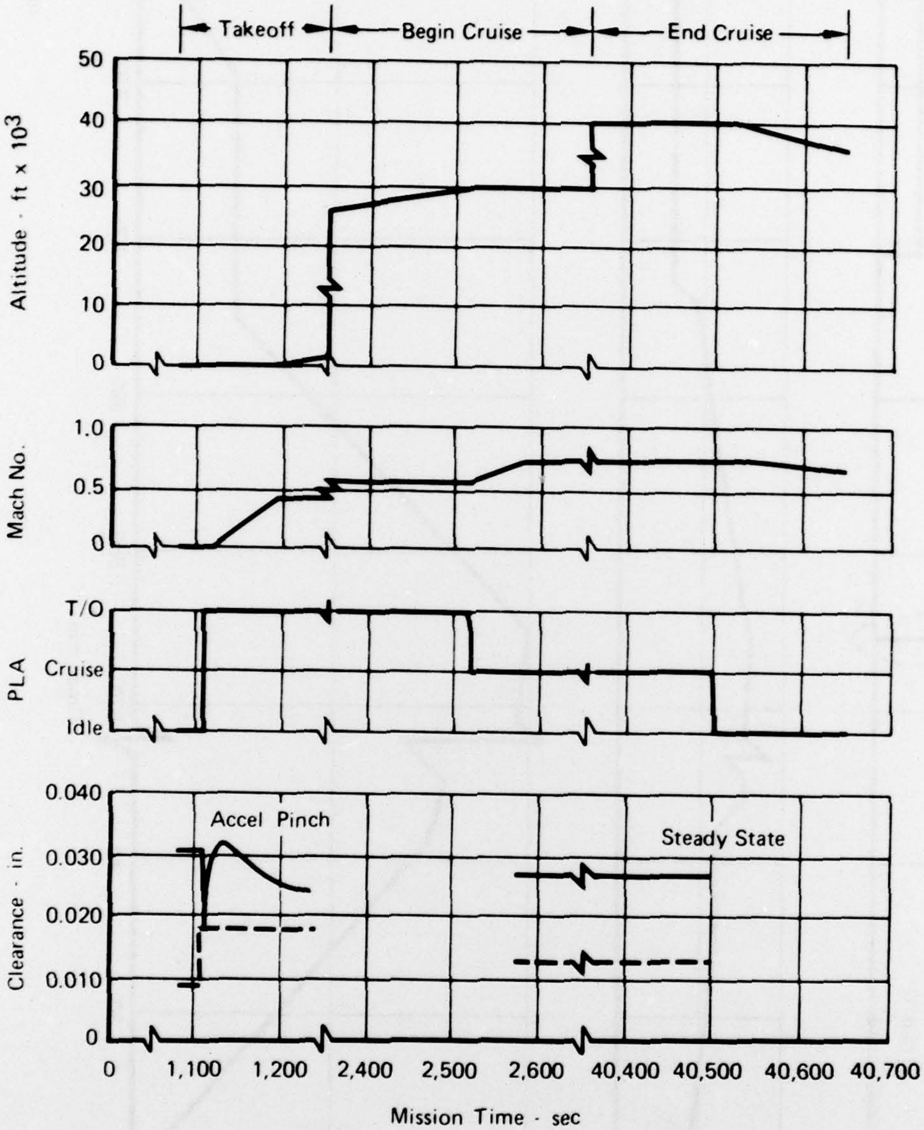

Figure 112. Transport HPT 1st Blade Tip Baseline Clearance History

TABLE 22. MAXIMUM THERMAL ROTOR—TO—CASE MOTION

Stage	Relative Motion
Fighter-Combat Transient	
8th HPC	0.037
13th HPC	0.026
1st HPT	0.046
Transport-Takeoff Transient	
8th HPC	0.026
13th HPC	0.018
1st HPT	0.027
4th LPT	0.044

TABLE 23. MANEUVER AND SURGE MISSION DATA

Operating Condition	*Vert g's*	*Horiz g's*	*Pitch and Rate*	*Yaw Rate*	*Surge*
Fighter Mission					
Takeoff	2.0	0.5	0.2	0.15	No
Cruise	2.2	0.5	0.10	0.10	No
Combat	6.0	0	0	0.16	Yes
Transport Mission					
Takeoff	2.0	0.5	0.2	0.15	No
Cruise	2.2	0.5	0.10	0.10	No

TABLE 24. MANEUVER AND SURGE DEFLECTIONS

Stage	*Maneuver Deflection*	*Surge Deflection*	*Total*
Fighter Takeoff			
8th HPC	0.003	0	0.003
13th HPC	0.003	0	0.003
1st HPT	0.004	0	0.004
Fighter Cruise			
8th HPC	0.003	0	0.003
13th HPC	0.003	0	0.003
1st HPT	0.004	0	0.004
Fighter Combat			
8th HPC	0.006	0.014	0.020
13th HPC	0.007	0.015	0.022
1st HPT	0.009	0.011	0.020
Transport Takeoff			
8th HPC	0.004	0	0.004
13th HPC	0.003	0	0.003
1st HPT	0.004	0	0.004
4th LPT	0.005	0	0.005
Transport Cruise			
8th HPC	0.003	0	0.003
13th HPC	0.003	0	0.003
1st HPT	0.004	0	0.004
4th HPT	0.005	0	0.005

Ovalization due to thermal effects was previously determined to be small on P&WA fighter engines. Effects on transport engines were included based on transport experience and advanced studies. In general P&WA's use of stacked rather than split cases and, in particular, the exclusive use of stacked or full ring cases in this study removes one of the prime causes of thermal ovalization and allows for an overall clearance improvement. The magnitude of the clearance losses due to these ovalization mechanisms are shown in Table 25.

The effects of vibration, bearing clearances, and tolerances were evaluated based on the advanced configuration of this study and previous engine experience. The numerical value for these effects are shown at representative stages for both missions in Table 24.

Performance losses due to deterioration occur primarily on the HPT.This component is particularly sensitive because of the large change in TSFC with clearance and the significant clearance deterioration which can occur in the severe HPT environment. The mechanism principally responsible for these losses is deterioration of the blade tip clearance.

Calculation of Operating Clearances and Required Operating Clearances. The operating clearance for each operating condition was obtained from the build clearance and thermal closedown at each stage. Knowledge of the effects of vibration, maneuvers, loads, etc., allowed the clearances available for closedown to be obtained. The available clearances were the difference between the operating and required clearances. The required and available operating clearances at the S/S fighter and transport mission points are shown and compared in Table 26.

TABLE 25. OVALIZATION, VIBRATION, BEARING CLEARANCE AND TOLERANCES FOR THE FIGHTER AND TRANSPORT ENGINES

Stage	*Bearing Clearance Vibration Build Tolerances (in.)*	*Ovalization Bending, Thrust Thermal (in.)*	*Total*
Fighter			
8th HPC	0.006	<0.001	0.006
13th HPC	0.006	<0.002	0.006
1st HPT	0.009	<0.001	0.009
Transport — Takeoff			
8th HPC	0.006	0.003	0.009
13th HPC	0.007	0.004	0.011
1st HPT	0.009	0.004	0.013
4th LPT	0.011	0.007	0.018
Transport — Cruise			
8th HPC	0.006	<0.001	0.006
13th HPC	0.007	0.001	0.008
1st HPT	0.009	0.001	0.010
4th LPT	0.011	0.001	0.017

TABLE 26. REQUIRED AND AVAILABLE OPERATING CLEARANCES

Operating Condition	*Stage*	*Operating Clearance*	*Required Clearance*	*Available Clearances*
Fighter Cruise	8th HPC	0.038	0.009	0.029
	13th HPC	0.036	0.010	0.026
	1st HPT	0.048	0.013	0.035
Fighter Dash	8th HPC	0.033	0.009	0.023
	13th HPC	0.036	0.010	0.026
	1st HPT	0.043	0.013	0.030
Transport Cruise	8th HPC	0.013	0.009	0.003
	13th HPC	0.011	0.010	0.001
	1st HPT	0.023	0.013	0.010
	4th LPT	0.050	0.020	0.033

Clearance Results. The attainable benefits of the various ACC schemes are listed in Table 6. These benefits were calculated from data available on clearances and amount of closedown achievable with each scheme type. The results represent the different groupings and stages considered previously.

SECTION 3
SUMMARY AND CONCLUSIONS

3.1 PROGRAM SUMMARY

The program objective was to evaluate the potential for active clearance control (ACC) on future military fighter and transport aircraft/engines, rank the candidate schemes, and recommend a future course of action.

Potential ACC concepts were obtained from a review of the open literature, patent disclosures, P&WA literature, and brainstorming sessions. Fifty-one schemes were uncovered which could potentially control blade tip and other engine sealing clearances. These schemes were reduced to twelve by systematically combining similar schemes and eliminating unworkable and less effective schemes. The resulting five mechanical, two pneumatic, and five thermal schemes are shown in Figures 52, 53 and 54.

The fighter and transport missions selected were the Advanced Tactical Fighter (ATF) and the C141X strategic aircraft. The ATF is a 50,000 lb takeoff gross weight (TOGW) class single engine aircraft with a 5,000 lb payload, and a high-altitude cruise out, low-altitude supersonic dash to combat mission. The C141X is a potential C141 replacement in the 380,000 lb TOGW class with 4 engines, a 68,000 lb payload, 5,000 mile range and requiring an 8,000 ft runway. The corresponding engines for these aircraft were an advanced F100 for the fighter and an F100-cored high-bypass-ratio (HBPR) turbofan for the transport. Both were rubber engines having the same core, but were scaled separately to meet their respective thrust requirements.

Three levels of controls for ACC were considered: simple on/off two-position for the cruise or cruise/dash legs only, open loop feedback infinitely variable for the climb/cruise/dash legs, and closed loop feedback (requiring a clearance sensor) applicable over the entire mission. On/off systems were selected because the majority of the benefit is obtained at cruise/dash for both missions, and the open and closed loop systems had positioning and reliability uncertainties.

The criteria selected to evaluate the different schemes were net Life Cycle Cost benefits (ΔLCC) to the fleet over the life of the weapons system. These criteria were based on a new-engine/new-aircraft application where efficiency improvements due to ACC were used to reduce aircraft and engine size for a fixed mission (range, payload, etc.). The detailed operation and impact (cost, weight, reliability, maintainability) of the 12 final schemes were evaluated by adopting each of the candidate schemes to selected stages in the base engines. The effectiveness and net payoff of each scheme on each engine were evaluated for the HPC, HPT, and LPT.

The baseline available clearances were calculated for both transient and steady-state mission legs. Clearances consistent with drum rotor and straddle mounted HPT were assumed, as were advanced engine mounting techniques such as symmetric thrust take-out and cowl load sharing.

Influence coefficients were used to calculate the effects of clearance improvements on system performance and LCC. These coefficients were generated assuming the engine and aircraft would be resized and reproportioned as a result of component efficiency changes. A comparison of these coefficients for the different engines and components showed that for the same clearance change on any component, the transport ΔLCC improvement was about twice that of the fighter. For both missions the variation between components was in the proportion 2:4:1, HPC:HPT:LPT. For the transport two stage, 0.01-in. clearance closedown in both stages was worth a total of $50M.

3.2 CONCLUSIONS

A summary of the most promising ACC schemes (based on LCC savings) is shown in Tables 27 and 28.

TABLE 27. TRANSPORT – MOST PROMISING ACC SCHEMES BASED ON LCC CHANGE

Scheme Name		Scheme No./Page	LCC Change* (Millions)
HPC Stage 6-9			
Thermal	N/A		
Mechanical	Strap Shroud	8/44,46	+33
Pneumatic	Pneumatic Segmented Shroud	9/46	+24
HPC Stages 10-13			
Thermal	Case Cooling	31/45,46	+14
Mechanical	Strap Shroud	8/44,46	+35
Pneumatic	Pneumatic Segmented Shroud	9/46	+16
HPT Stages 1 and 2			
Thermal	Case Cooling	31/45,47	–37
Thermal	Case Heating	22A/45,47	–38
Thermal	Heated and Cooled Supports	32/45,46	–30
Mechanical	Cam Shroud	33/43,44	– 2
Pneumatic	N/A		
LPT Stages 3-7			
Thermal	Case Cooling	31/45,47	– 8
Mechanical	Strap Shroud	8/44,46	+ 8
Pneumatic	N/A		

*Negative sign denotes a payoff.

TABLE 28. FIGHTER – MOST PROMISING ACC SCHEMES BASED ON LCC CHANGE

Scheme Name		Scheme No./Page	LCC Change* (Millions)
HPC Stage 6-9			
Thermal	N/A		
Mechanical	Strap Shroud	8/44,46	+10
Pneumatic	Segmented Shroud	9/46	– 4
HPC Stages 10-13			
Thermal	Heated Case	22A/45	+28
Thermal	Case Cooling	31/45	+28
Mechanical	Strap Shroud	8/44,46	+ 3
Pneumatic	Pneumatic Segmented Shroud	9/46	– 5
HPT			
Thermal	Heated and Cooled Supports	32/45	–37
Mechanical	Cam Shroud	33/44	–26
Pneumatic	N/A		
LPT			
Thermal	Heated and Cooled Supports	32/45	+ 2
Mechanical	Strap Shroud	8/44,46	+ 6
Pneumatic	N/A		

*Negative sign denotes a payoff.

3.2.1 Fighter Application

For the fighter application, ACC showed a significant net benefit in the HPT only. The best schemes for this application were the thermal two-position high pressure air scheme "heated and cooled supports" and the mechanical two-position "cam actuated shroud."

The principal reason for the HPT being the only component to have a significant payoff is the combination of large available clearances and a large influence coefficient factor. The available clearances on other components were in the same range as the HPT, but the influence coefficient factor is substantially less; therefore, the efficiency gain is reduced. The acquisition and maintenance costs of ACC on the two-stage HPT were generally comparable to the cost for the two-stage LPT, and somewhat lower than the cost for either of the two 4-stage arrangements considered on the HPC.

The net savings for the fleet were \$37M and \$26M ΔLCC for these schemes respectively. The savings were significant and are sufficient to justify further development of ACC for the fighter application. Although the thermal scheme had a larger net payoff than the mechanical scheme, the difference was not significant enough to conclude that the thermal scheme would be uniformly superior for other applications. The thermal scheme was simpler and cheaper but has a limited transient response which may cause difficulties in a fighter application. The mechanical scheme has a sufficient response for normal transients, but has potential problems with durability, wear, and friction. Based on the results of this analytical study the two HPT schemes are ranked equal for the fighter application, pending hardware evaluation.

3.2.2 Transport Application

ACC showed a significant net benefit in the transport HPT. On the low pressure turbine some schemes showed a net ΔLCC savings, but the amount of the savings was very small.

As in the fighter, the principal reason for the HPT being the only component to have a significant payoff is the combination of significant available clearances and a large influence coefficient factor. The smaller available clearances in the compressor and the smaller influence coefficient factor made ACC unattractive in the compressor. In the LPT the available clearance was twice that of the HPT, but the influence coefficient factor was only 1/3 that of the HPT. This lower performance benefit in combination with the higher acquisition and maintenance costs on a transport five-stage LPT compared to the fighter two-stage HPT made the net benefit of LPT ACC marginal for the transport LPT.

The ACC concepts with the largest payoff in the HPT were all thermal schemes. These were the case cooling scheme (\$37M), the case heating scheme (\$38M), and the heated and cooled supports scheme (\$30M). The potential savings were significant, particularly in light of the small clearances available for closedown in the transport HPT. The payoff was sufficient to justify further development of ACC for the transport application.

The heated and cooled supports and the case cooling schemes were equally rated somewhat above the case heating scheme.

3.2.3 Different Missions and Cycles Considerations

The net payoff for ACC will vary widely with the particular mission and cycle since the available clearance and ACC effectiveness are both highly dependent on the assumed mission and cycle characteristics. A different application which had a higher overall pressure ratio and required proportionately less power at cruise compared to takeoff could well expect to have significantly larger HPT clearances (in the *0.020* to *0.030* in. range) compared to the clearances of this study. This

would be true even for the advanced bearing and load configurations of this study. For this level of available clearances the net payoff for the transport fleet would increase substantially into $100M range. Significantly larger payoffs are possible for other advanced missions based on mission and performance effects. Although there is the possibility of greater payoff in ΔLCC for different missions and cycles as compared to the mission and cycle of this study program, the component payoff ranking should remain the same. That is, the HPT should produce the largest and most significant payoff.

3.2.4 New Aircraft/Engine Application vs Retrofit

An alternate approach to the new engine/aircraft assumption of this study would be a retrofit application where ACC was a bolt-on option to a fixed geometry engine and aircraft. For a transport retrofit the effectiveness of LPT ACC clearance changes increase significantly in importance with respect to the HPT. Limitations in the amount of closedown achievable with bolt-on thermal systems on the LPT compared to the HPT still result in the HPT having a larger payoff, however. In addition, the overall LCC benefits for a given clearance change are significantly smaller in both the HPT and LPT for the retrofit application compared to the new engine/aircraft application for the mission and cycle selected for this study.

3.2.5 Clearance Sensor Payoff

The lack of payoff for a clearance sensor is principally a result of the large portions of the mission (90% transport/70% fighter) assumed to be fully serviced by a simple on/off control system. All of the ACC benefits possible are gained with on/off control on these portions of the missions. No additional benefits are available for higher levels of control (open loop/feedback) to offset their greater cost, weight, and complexity, hence no apparent payoff.

This conclusion is specific to the framework of the study, with its particular assumed cycle, mission, and clearance ground rules. Both the transport and fighter engines are required to operate at high power levels throughout the cruise legs, and the calculated clearances were assumed to equal the actual engine clearances

Operation at high power levels throughout the mission results in relatively tighter clearances that are substantially unchanged over the cruise leg of the mission. For other missions where, if for example, the engine would be continually throttled back over the cruise leg, the clearances would continually change. Maintaining optimum clearances with ACC would then require a modulated clearance control, hence providing some payoff for open loop or feedback controls.

The available clearances of this study are based on a mean analysis assuming a typical engine, installation and history. The actual clearances on any one particular engine could however, be significantly different from the mean because of differences in hardware, installed environment, operating history, or calculation uncertainties. The development of a flight operational clearance sensor could be very useful in determining the magnitude of clearance variation due to these effects. If these variations proved to be significant, a clearance sensor used in a feedback control system would be useful if not required to fully benefit from ACC.

SECTION 4
RECOMMENDATIONS

Further development in the area of clearance control is recommended.

a. Additional analytical efforts to determine the effect of different missions and cycles on available clearances and performance payoff are recommended. The effects of one vs two-stage HPT and other similar comparisons are required. The effects should only be analyzed for the best schemes identified and for HPT application alone.

b. A parallel evaluation of the net payoffs for fully optimized passive clearance control in the HPT is suggested.

c. Pending the results of these two studies, a hardware demonstration of the selected ACC schemes is recommended.

ABBREVIATIONS AND SYMBOLS

ACC	Active Clearance Control
ATF	Advanced Tactical Fighter
BPR	Bypass Ratio
CET	Combustor Exit Temperature (°F)
HPC	High Pressure Compressor
HPT	High Pressure Turbine
LCC	Life Cycle Cost
LPT	Low Pressure Turbine
M	Million
N_2	High Rotor Speed (rpm)
OWE	Overall Weight Empty (lbs)
RCVV	Rear Compressor Variable Vanes
SL	Sea Level
TIT	Turbine Inlet Temperature (°F)
TOGW	Takeoff Gross Weight (lbs)
TSFC	Thrust Specific Fuel Consumption
W/S	Wing Loading (lbs/FT^2)
V_{jd}/V_{je}	Ratio of Core to Bypass Exit Velocities
$\Delta\lambda$	Failure Rate/1000 Flight Hrs
η	Efficiency
lb	Pound
CLR	Clearance (in.)
K	Thousand Feet

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